Neutrino Experiments

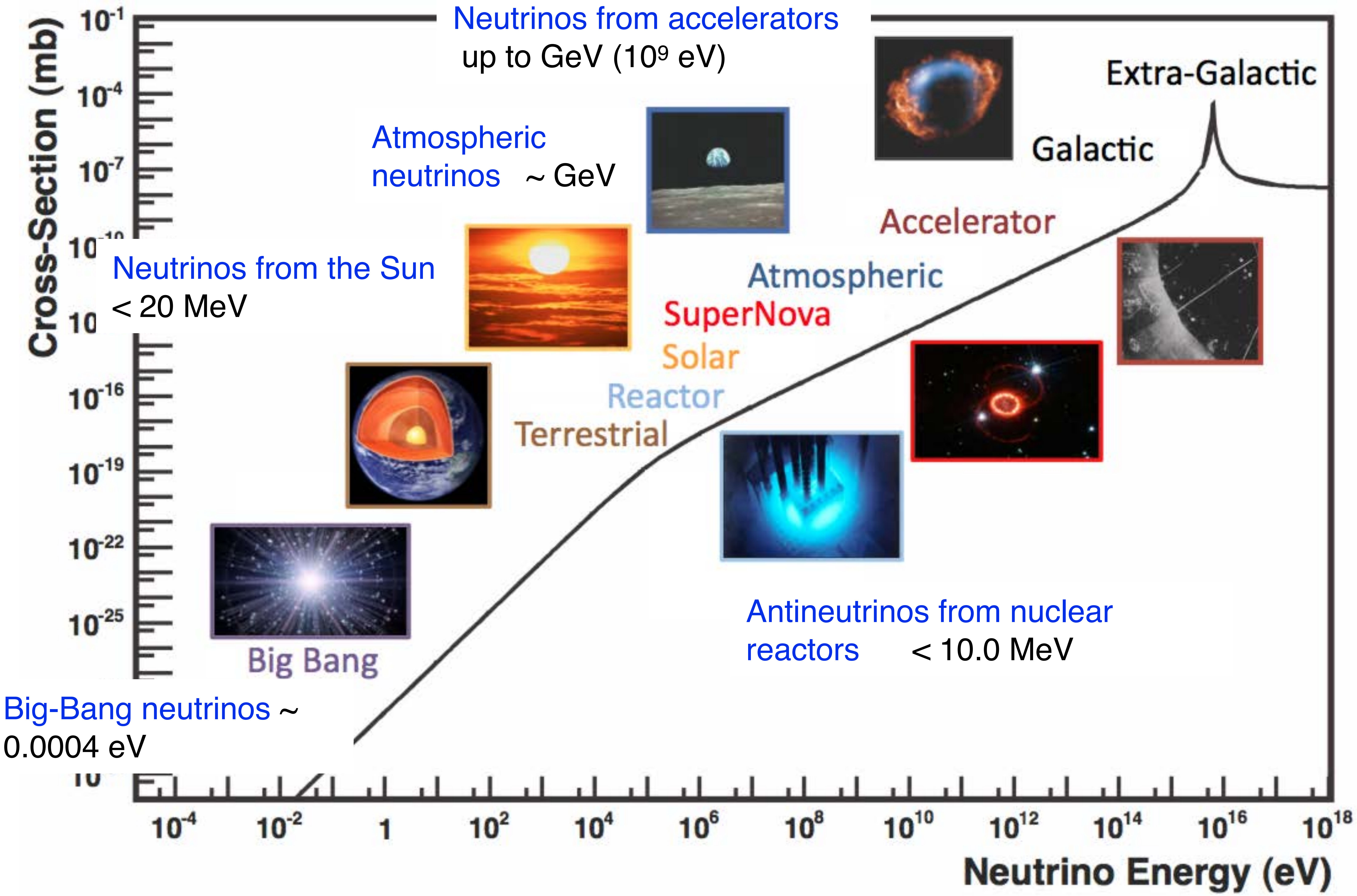
Opportunities for Discovery

Karsten Heeger
Yale University

July 3, 2023

Thanks to many colleagues
for slides and input!

Neutrinos in the Universe



Early Days of Neutrinos

1914, Chadwick

$N \rightarrow N' + e^-$ some nuclei emit electrons!

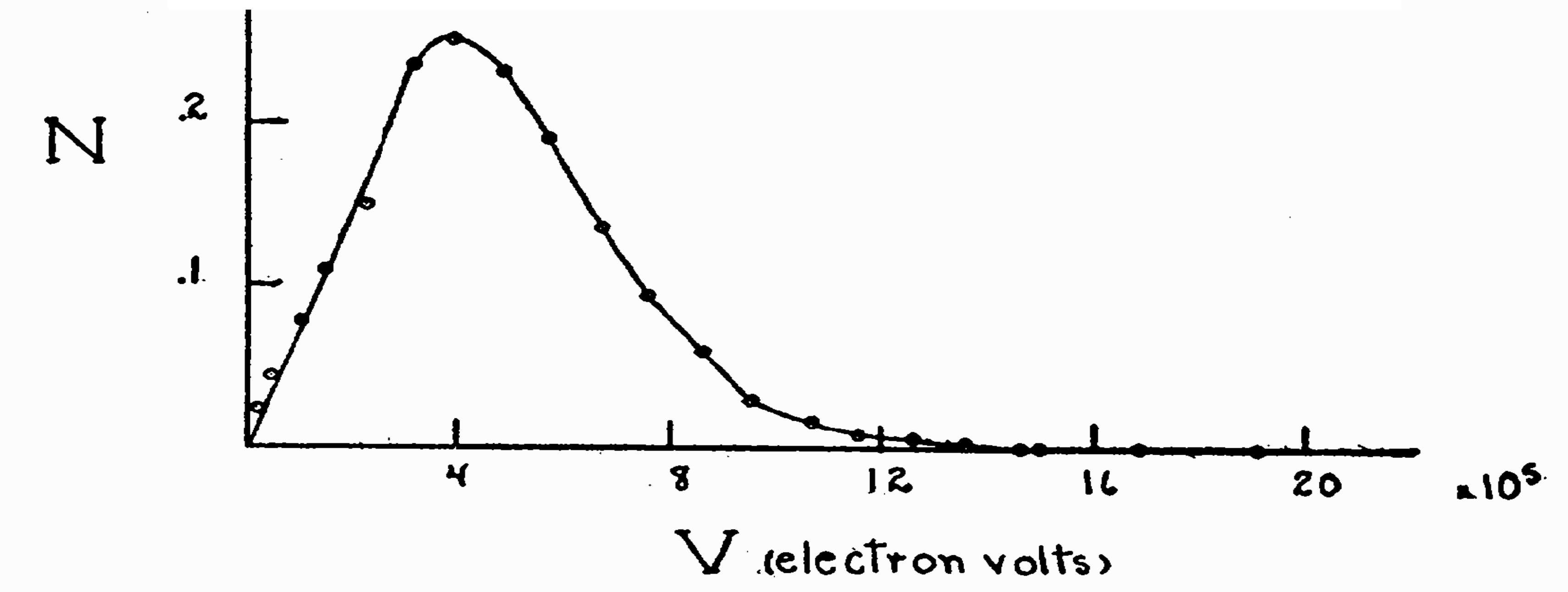
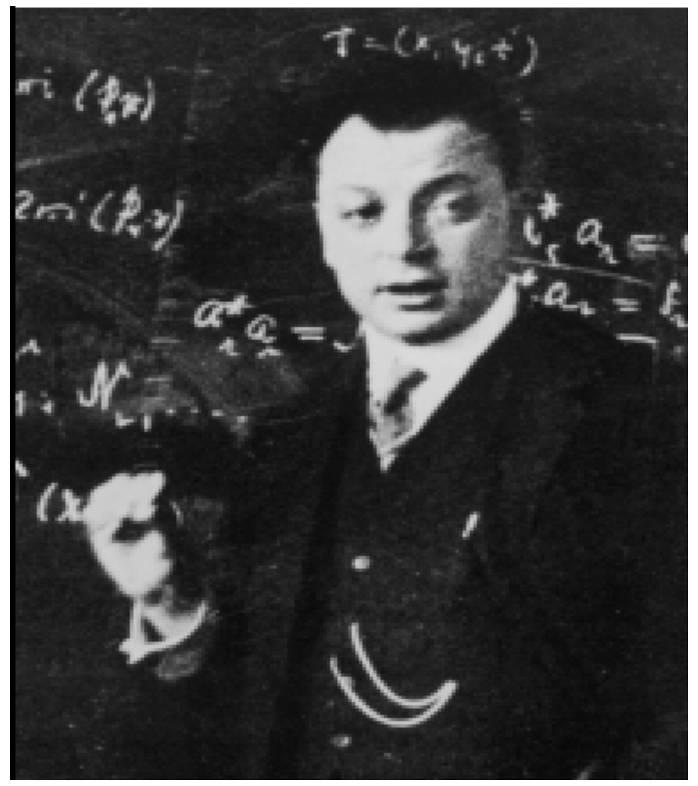
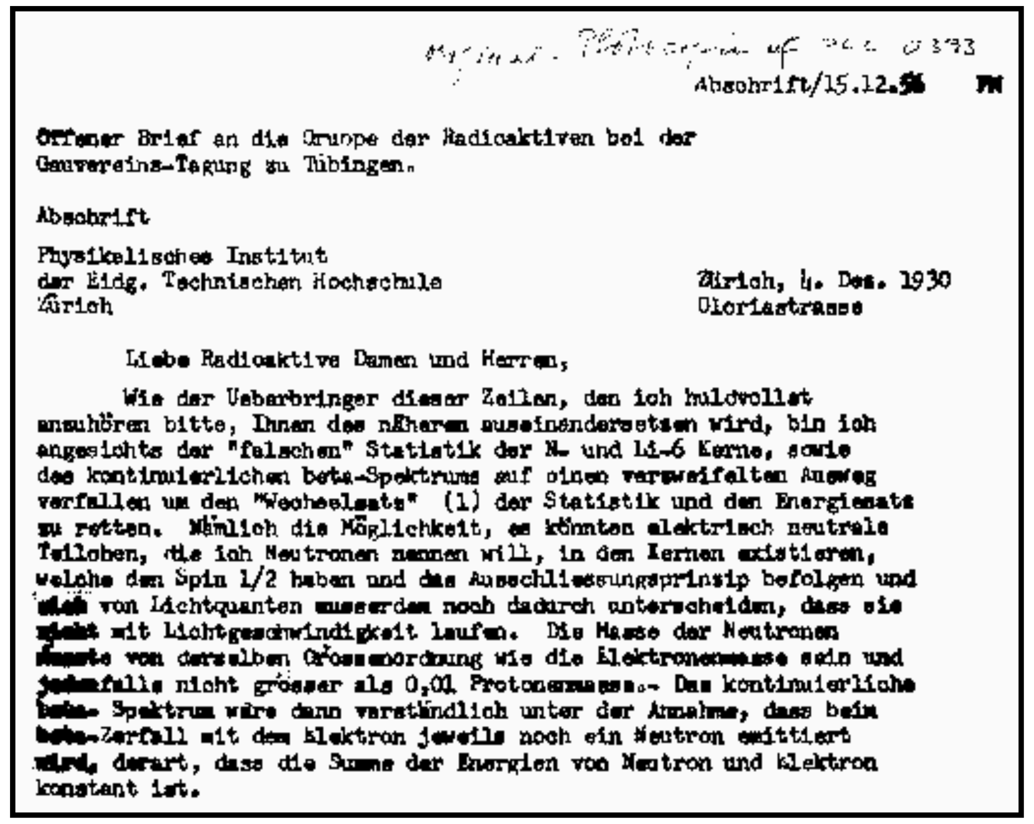


FIG. 5. Energy distribution curve of the beta-rays.

1930, Pauli





Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

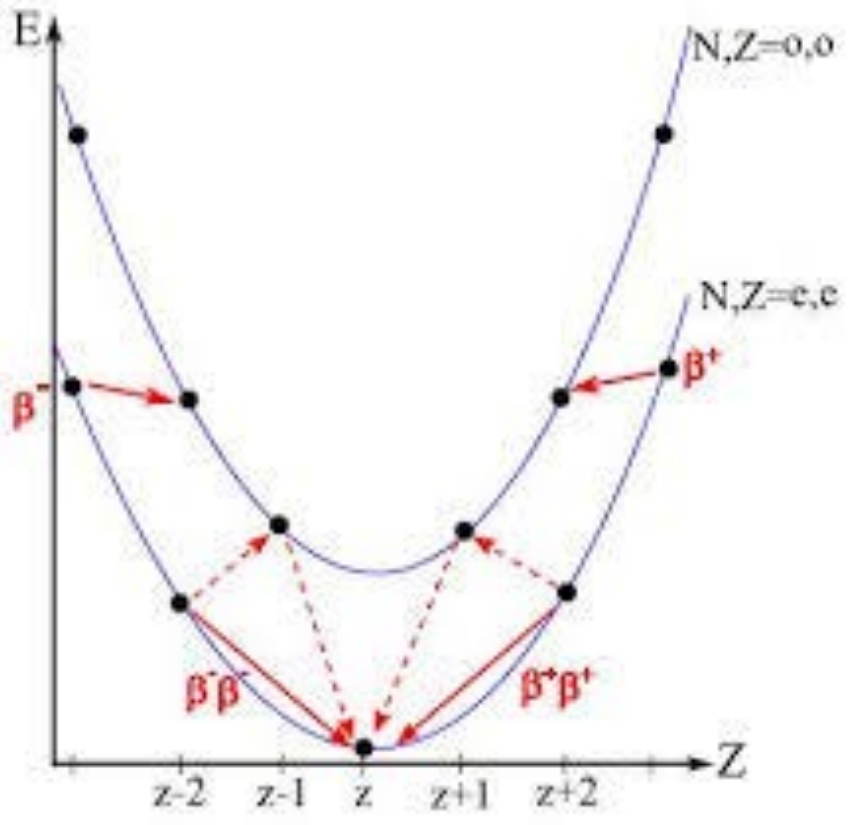
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

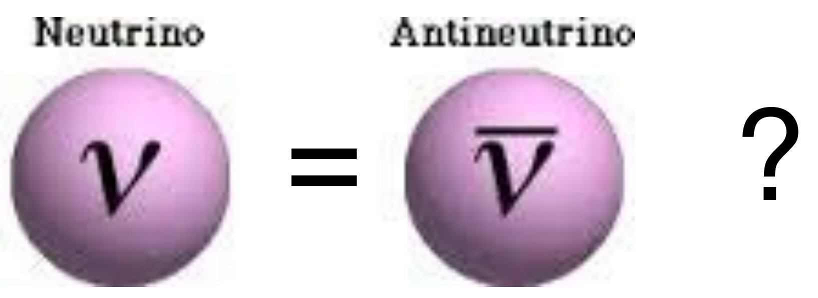
Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

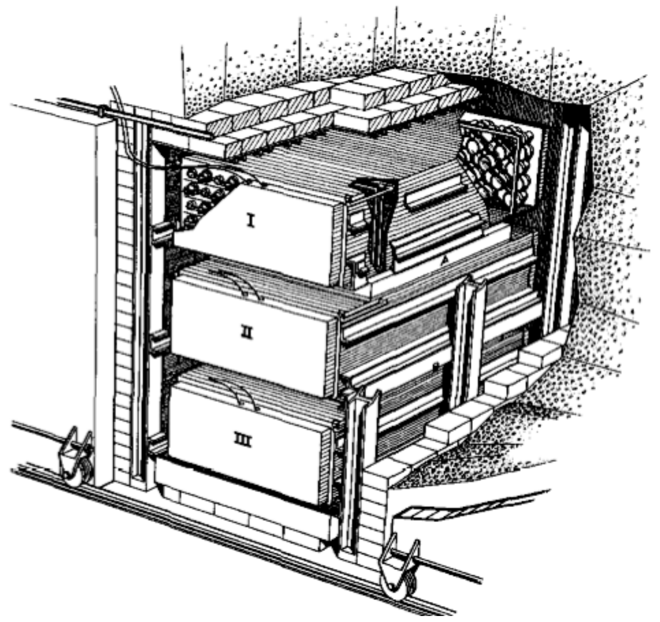
1935, Goeppert Mayer

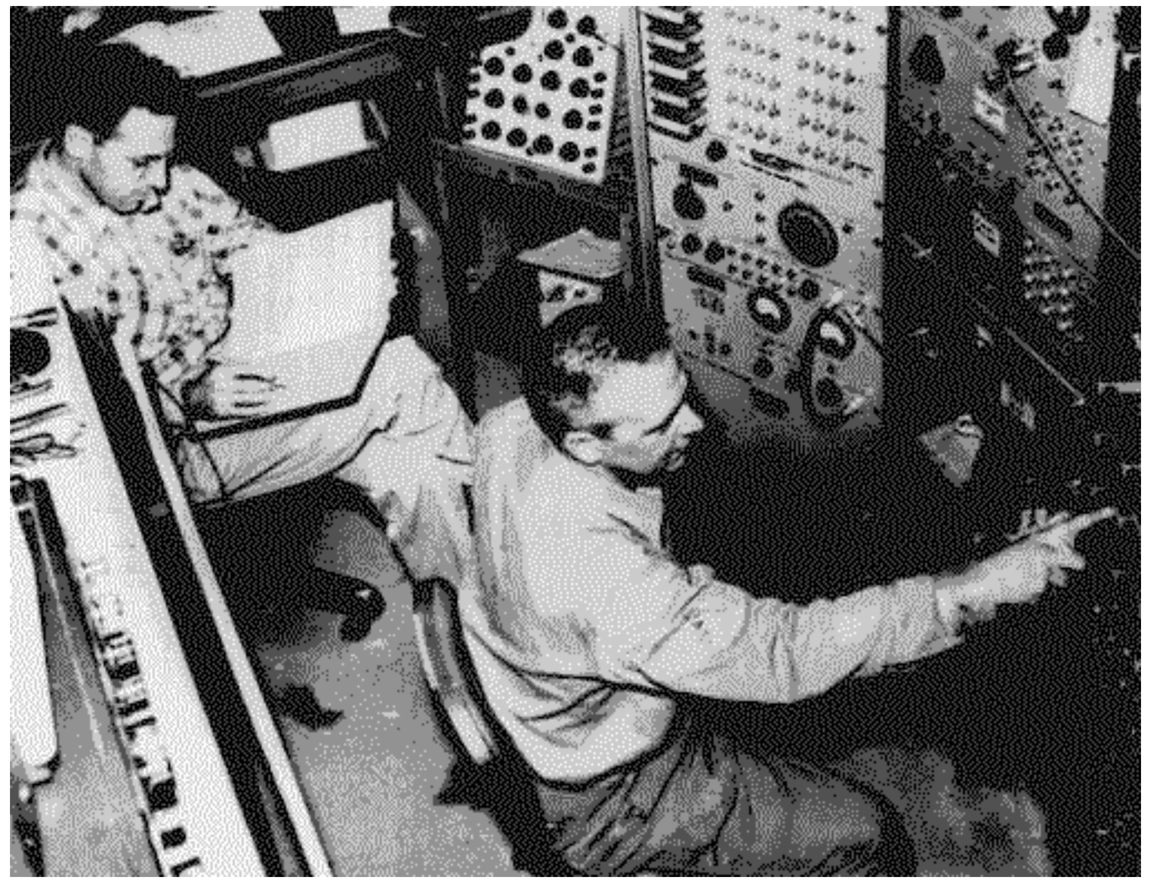


1937, Majorana



1956, Reines and Cowan,
"Observation of the Free Antineutrino"





Neutrino Physics is (almost) Impossible

532 NATURE April 7, 1934

Bethe

Peierls

The "Neutrino"

$$\bar{\nu} + p \rightarrow e^{+} + n$$

(Inverse beta decay)

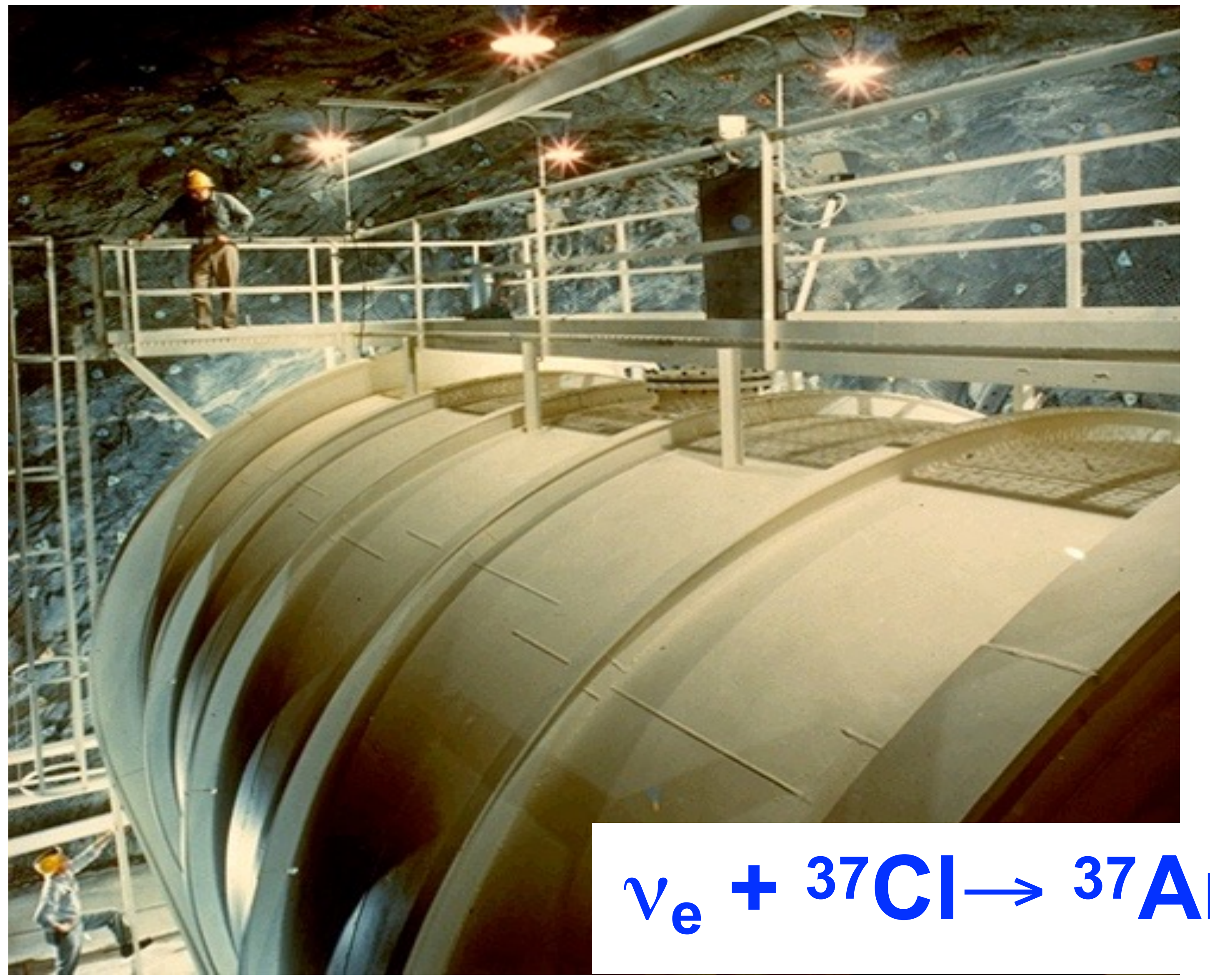
For an energy of $2 \cdot 3 \times 10^6$ volts, t is 3 minutes and therefore $\sigma < 10^{-44}$ cm.^{2} (corresponding to a penetrating power of 10^{16} km. in solid matter). It is

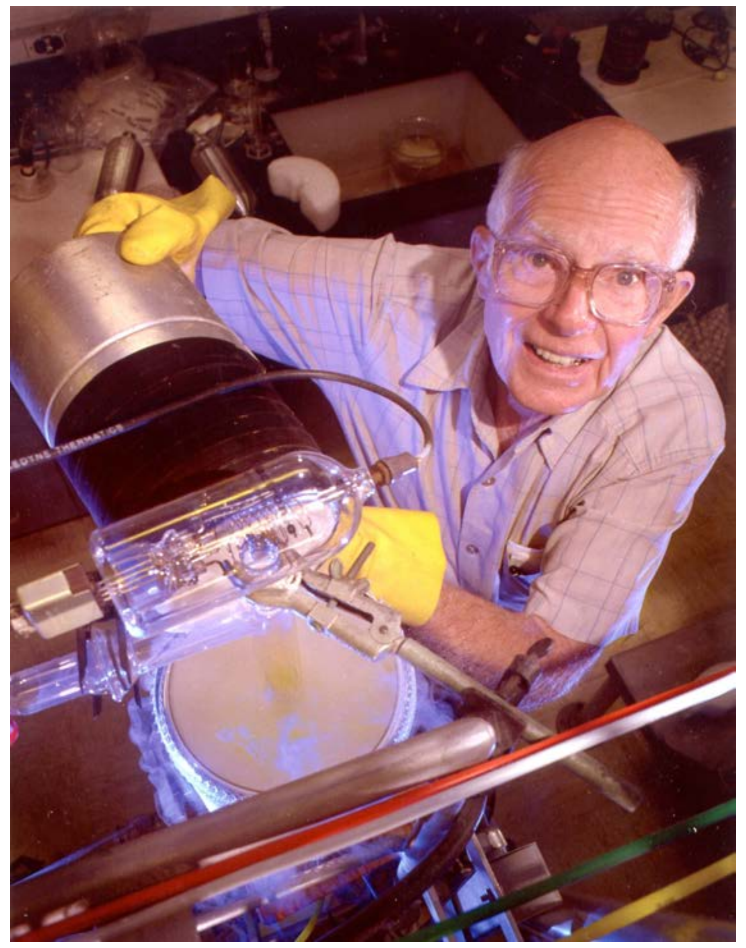
of the neutrino in nuclear transformations—one can conclude that there is no practically possible way of observing the neutrino.

H. Bethe.
R. Peierls.

Pioneering Experiments

Cl-Ar Solar Neutrino Experiment at Homestake

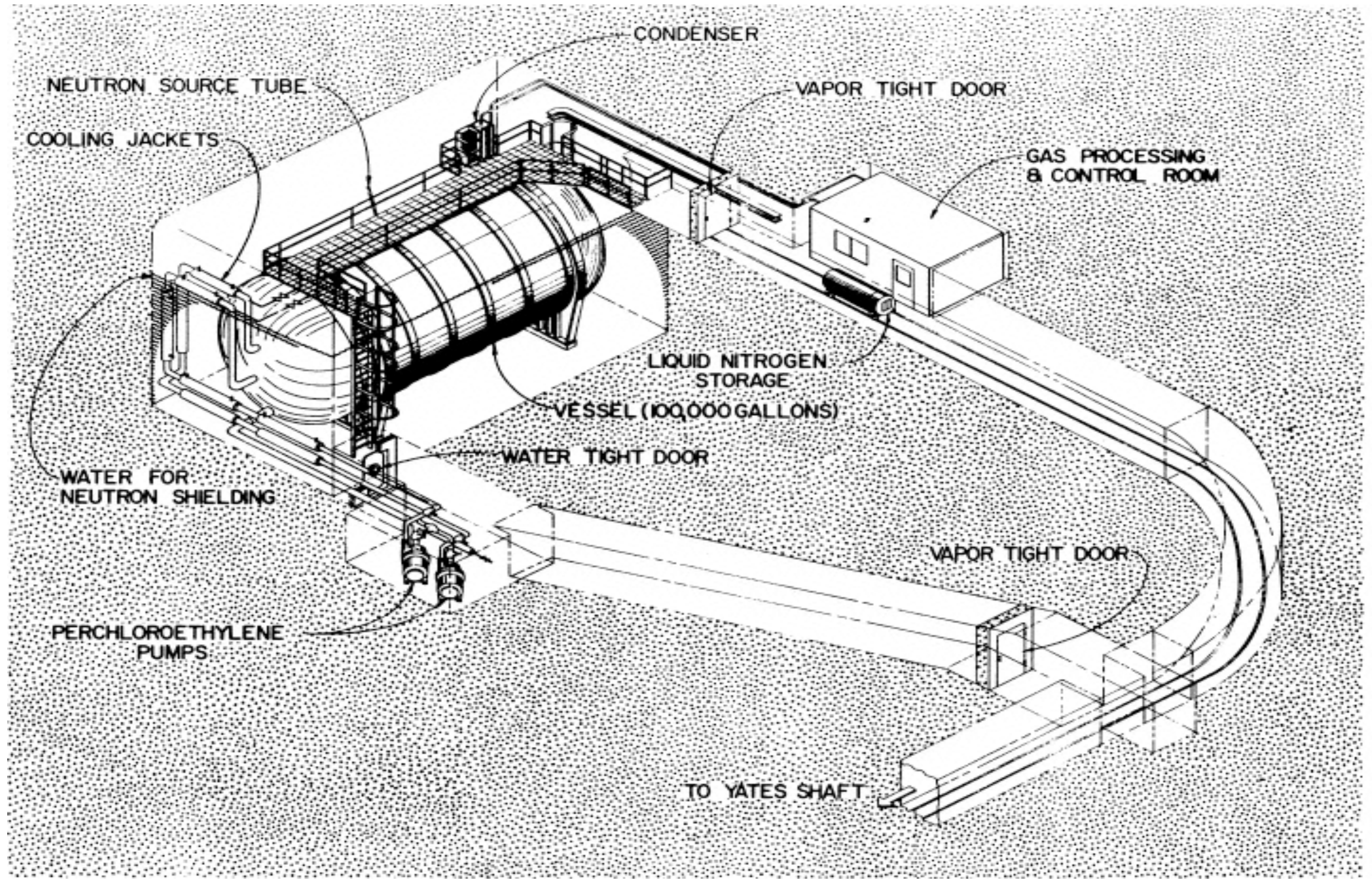


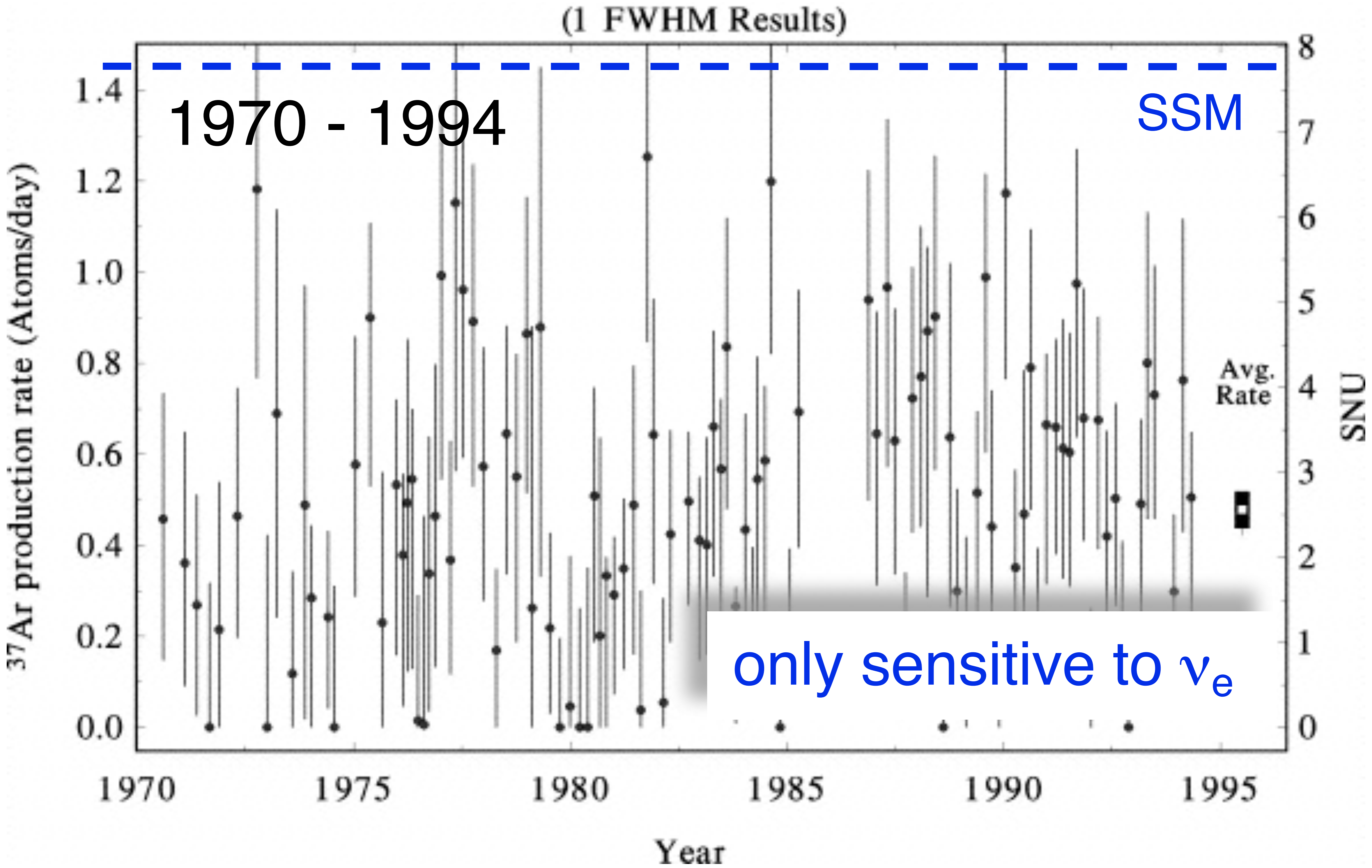


Ray Davis

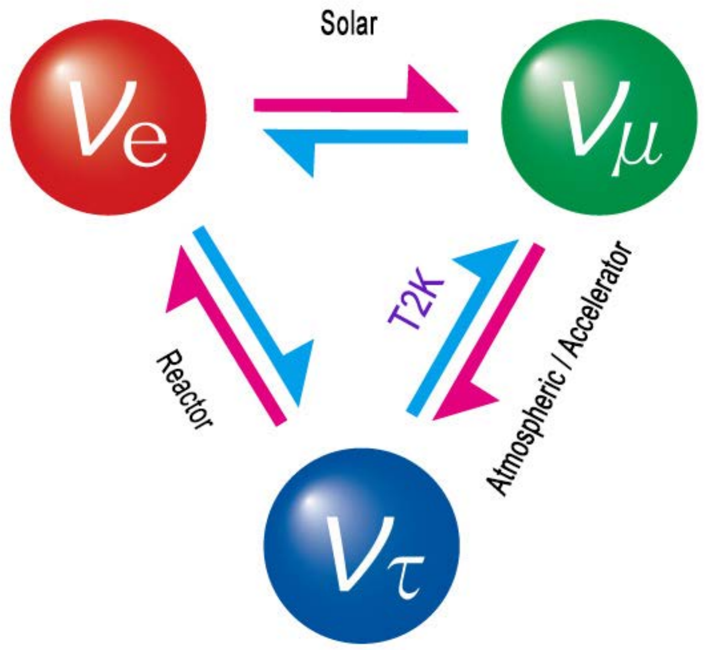
experimental talent
patience
persistence

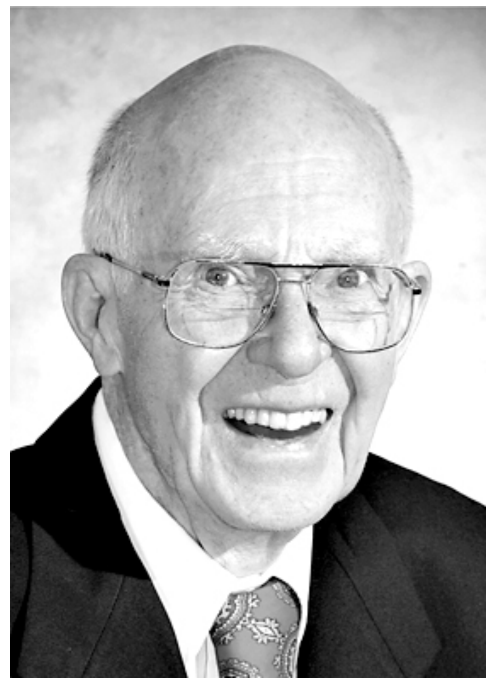
$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

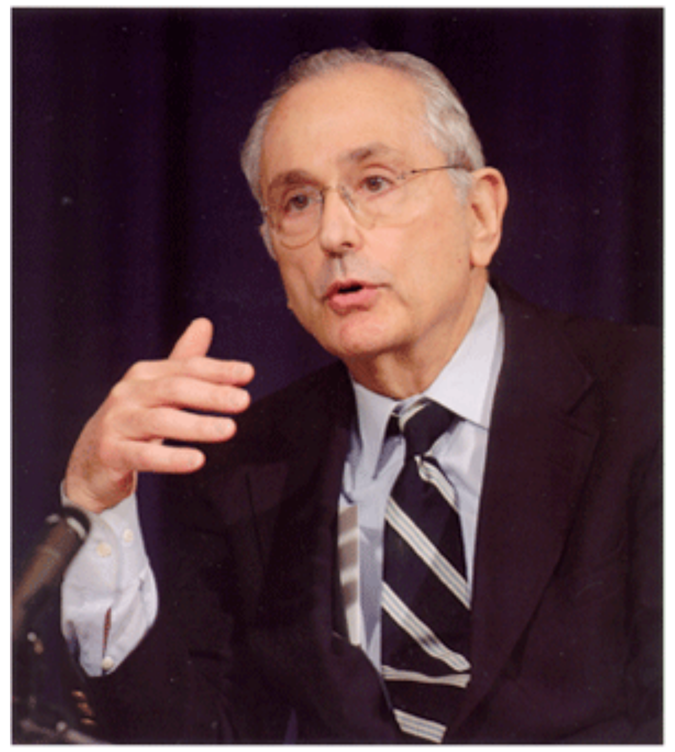




From Anomalies to Precision Oscillation Physics

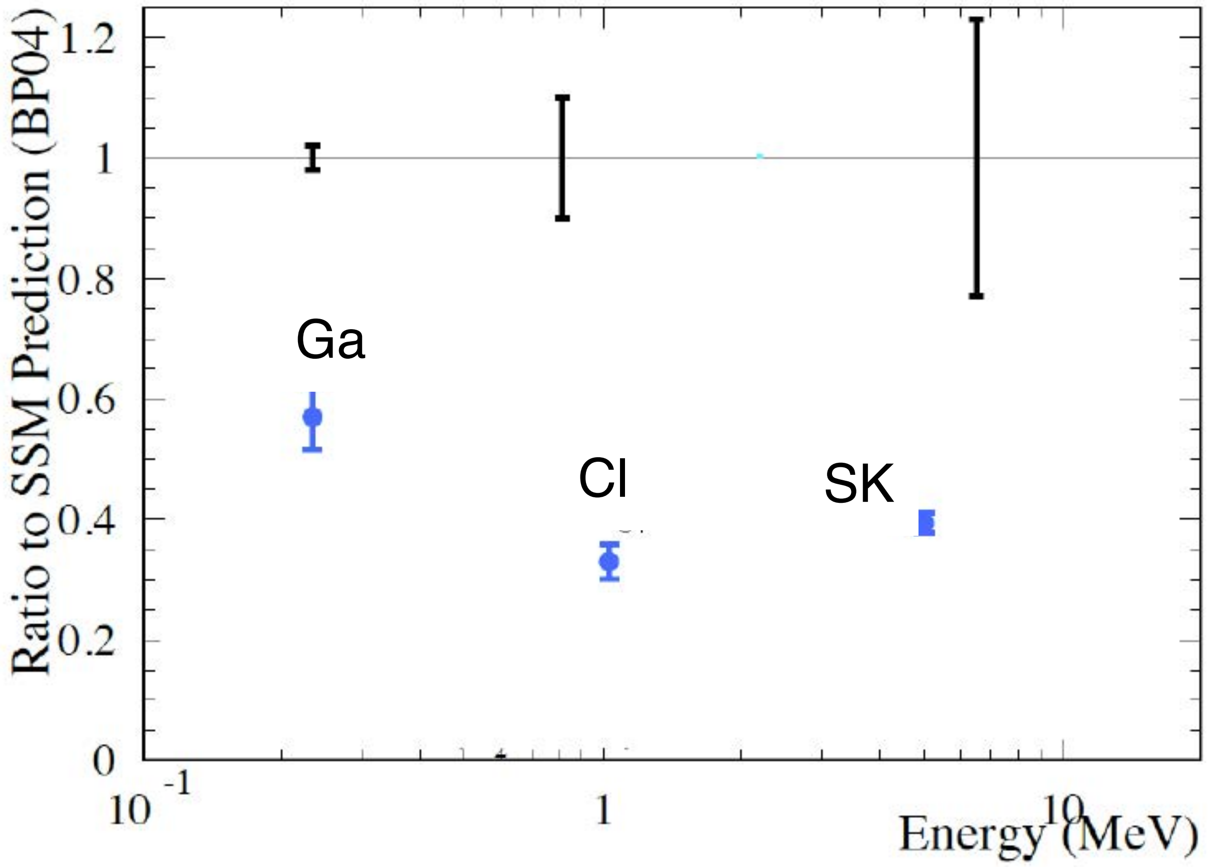






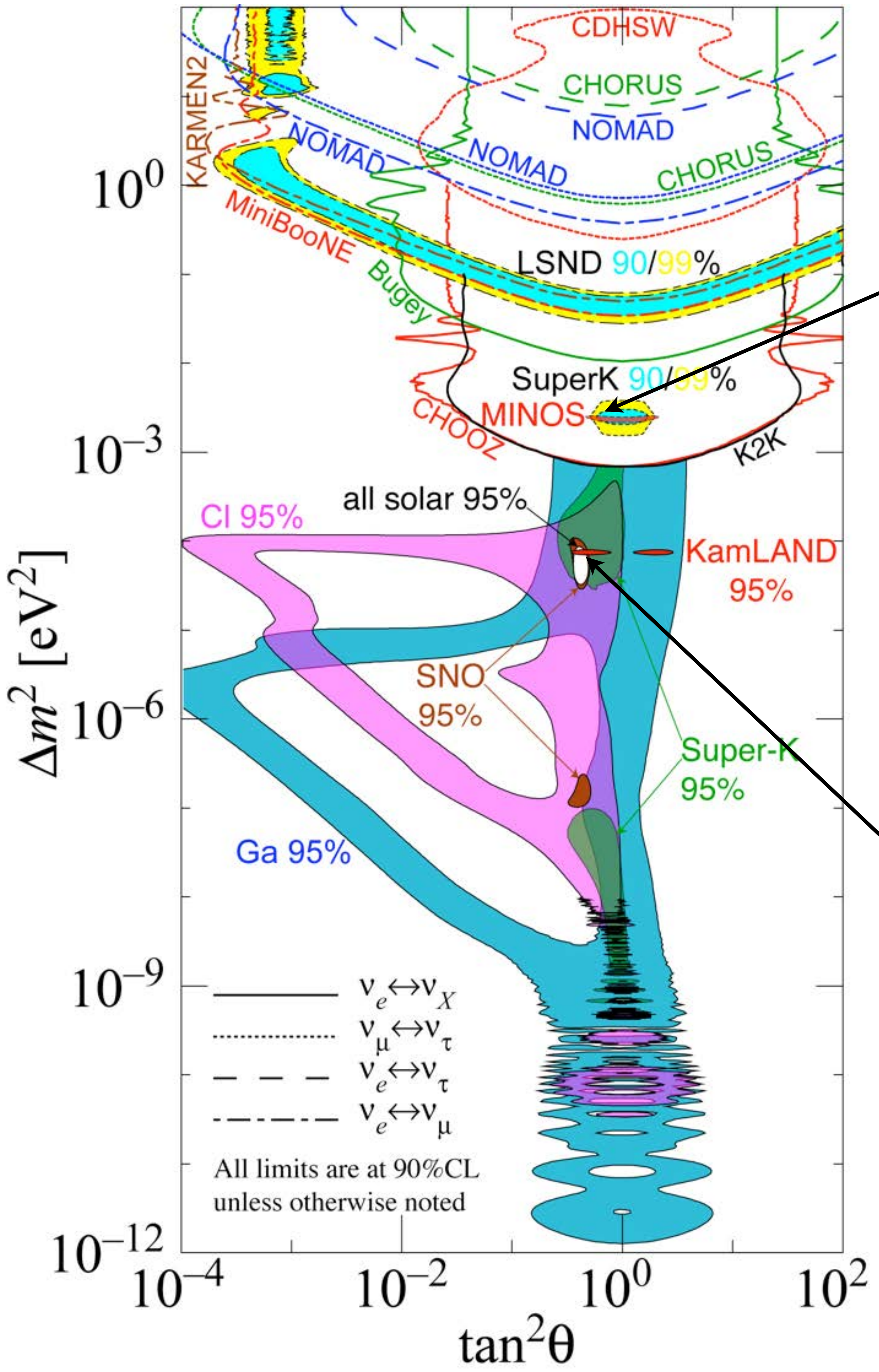
1960 -1990

solar neutrino problem



1990 - 2000

oscillation searches



http://hitoshi.berkeley.edu/neutrino

atmospheric/beam neutrinos

θ_{23}, Δm^2_{23}

solar/reactor neutrinos

θ_{12}, Δm^2_{12}

25 Years Ago - Discovery of Atmospheric Neutrino Oscillations

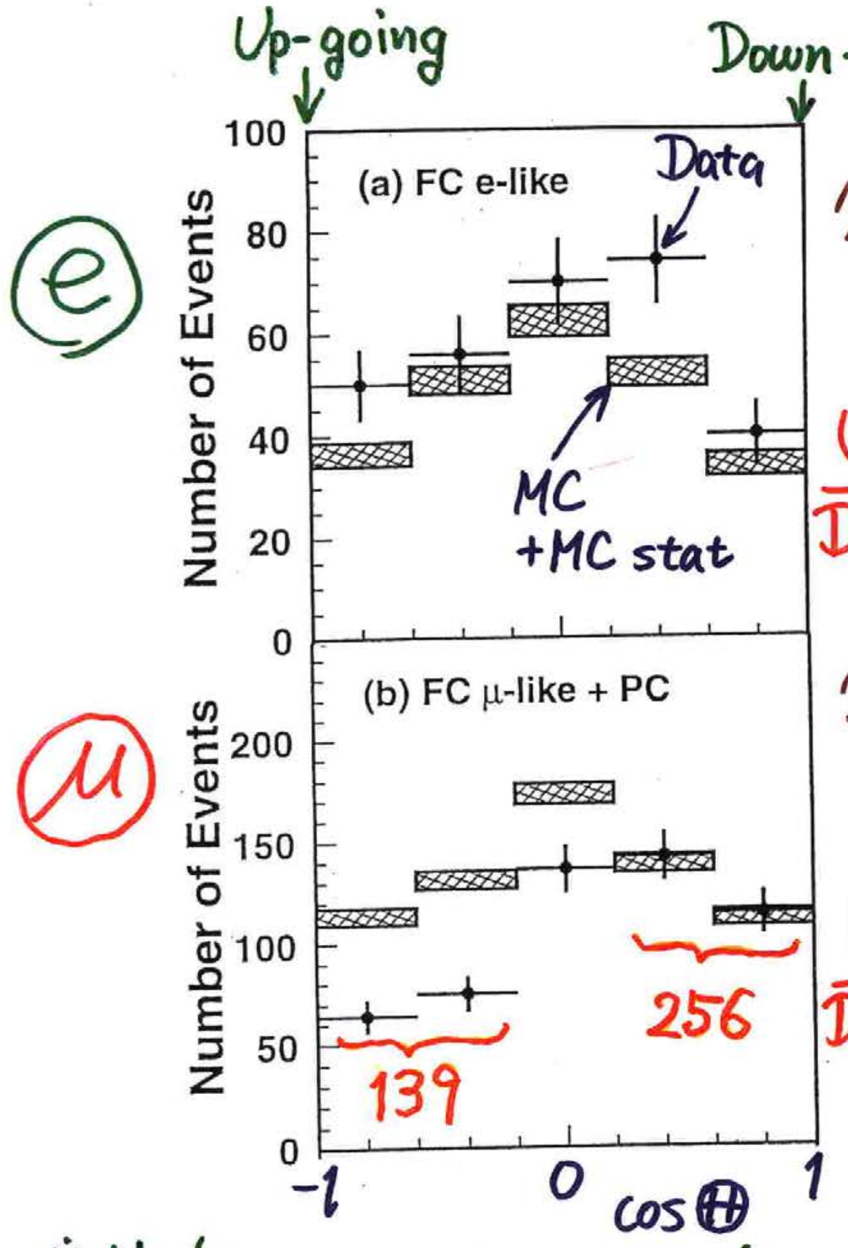
ν98, @Takayam
June 1998

Atmospheric neutrino results
from Super-Kamiokande & Kamiokand

— Evidence for ν_μ oscillations —

T. Kajita
Kamioka observatory, Univ. of Tokyo
for the {Kamiokande / Super-Kamiokande} Collaborations

Zenith angle dependence
(Multi-GeV)



χ^2(shape) $= 2.8/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.93^{+0.13}_{-0.12}$

χ^2(shape) $= 30/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.54^{+0.06}_{-0.05}$

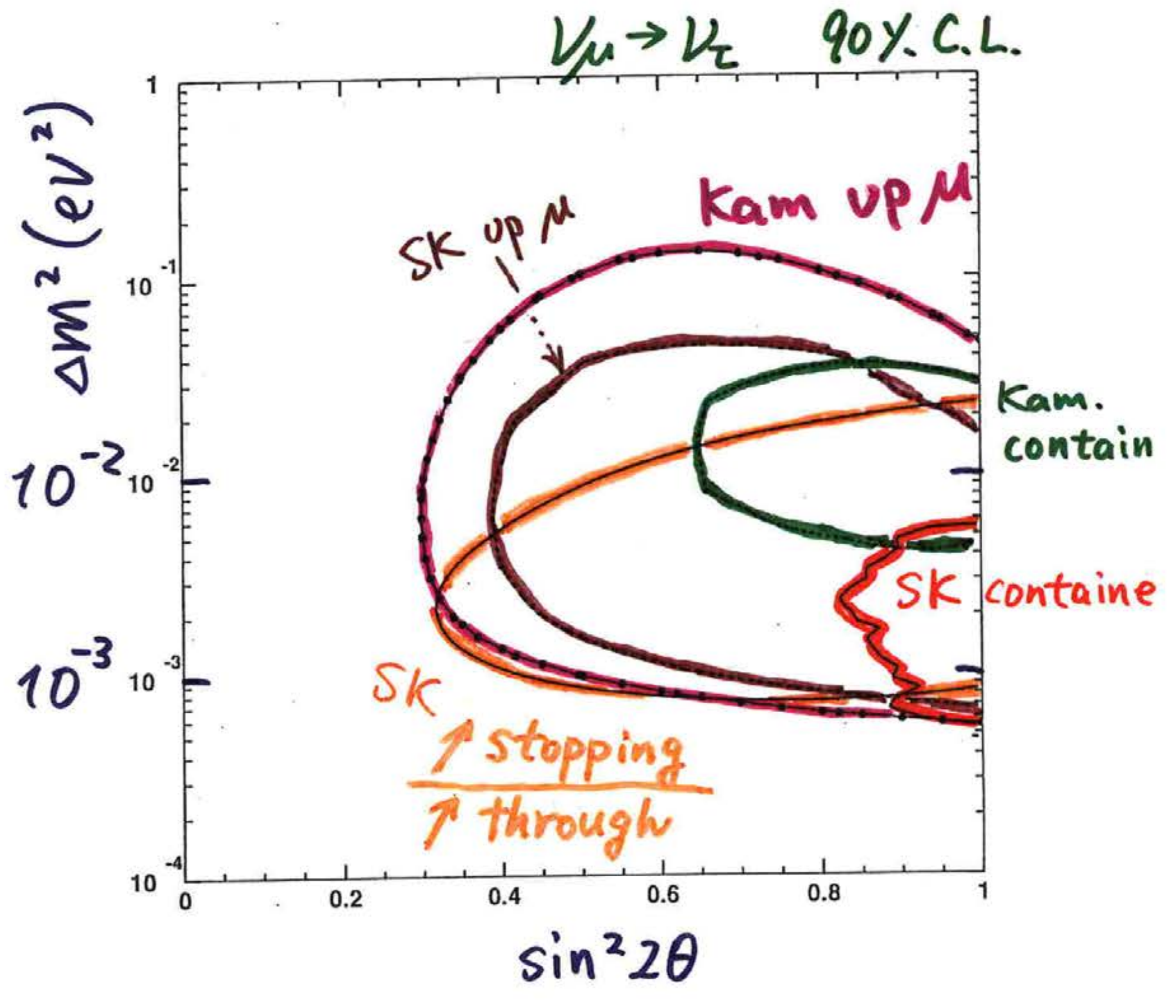
(6.2σ !!)

※ Up/Down syst. error for μ-like

Prediction (flux calculation …… $\lesssim 1\%$; 1km rock above SK …. 1.5%) 1.8%

Data (Energy calib. for ↑↓ …. 0.7%; Non ν Background …..< 2%) 2.1%

Summary
Evidence for ν_μ oscillations



- $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

(• $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$?)

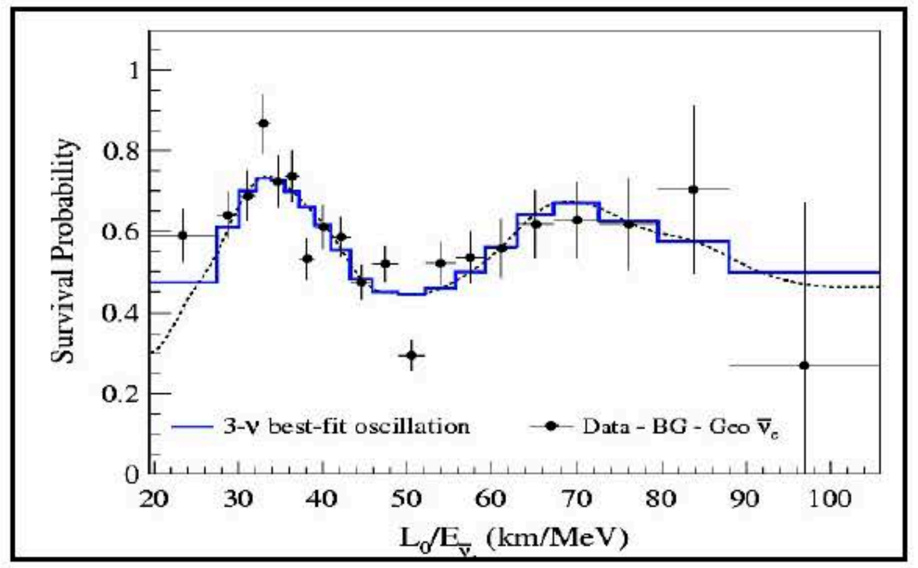
Neutrino 98

Neutrino Mixing

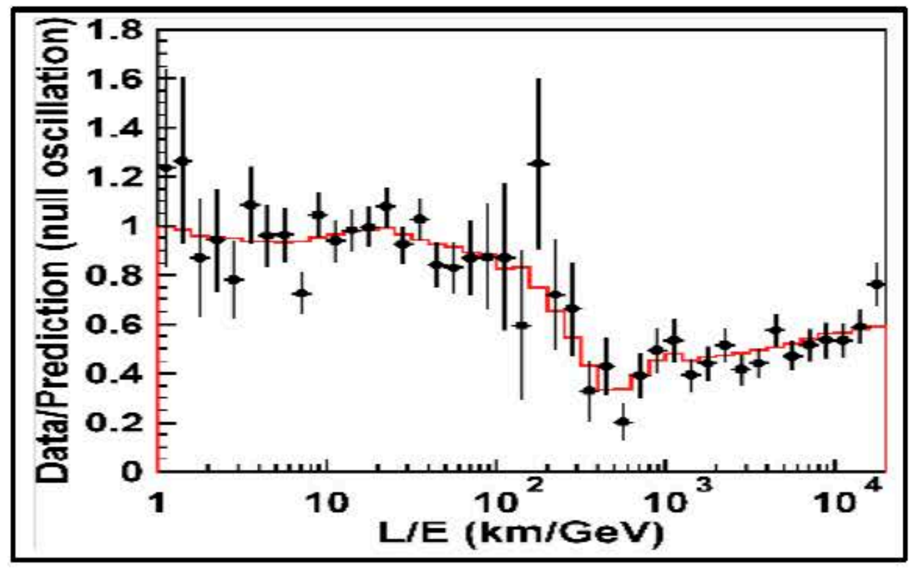
evidence for neutrino oscillations in many sources

reactor
solar
long baseline
atmospheric

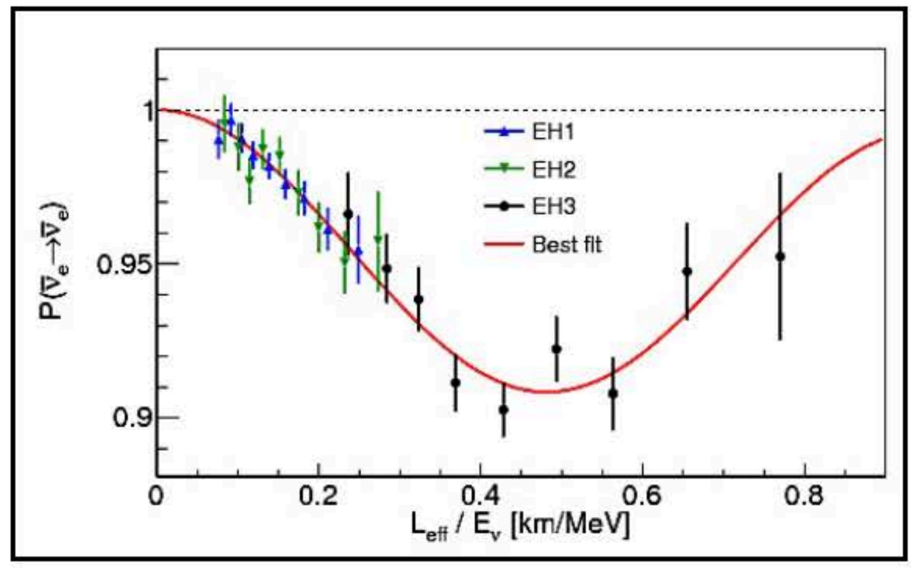
$e \to e$ $(\delta m^2, \theta_{12})$



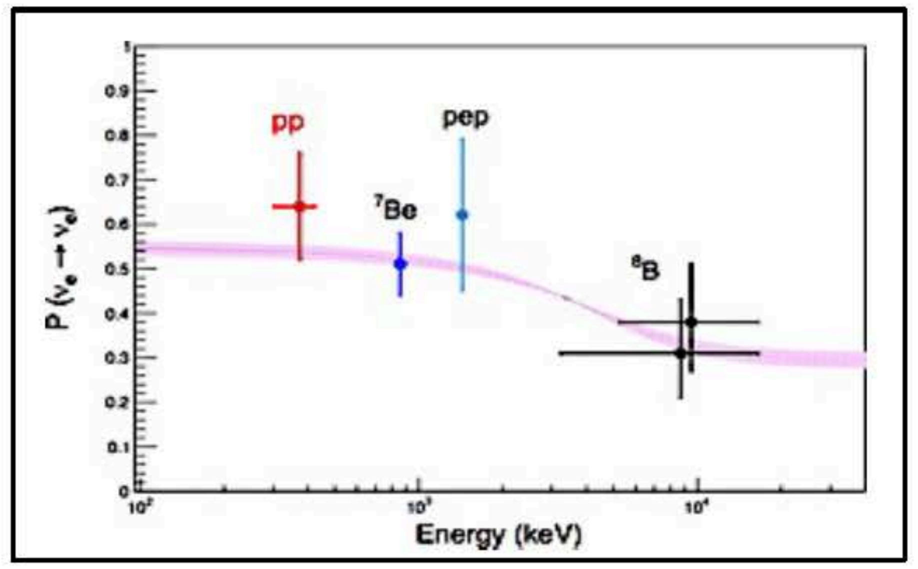
$\mu \to \mu$ $(\Delta m^2, \theta_{23})$



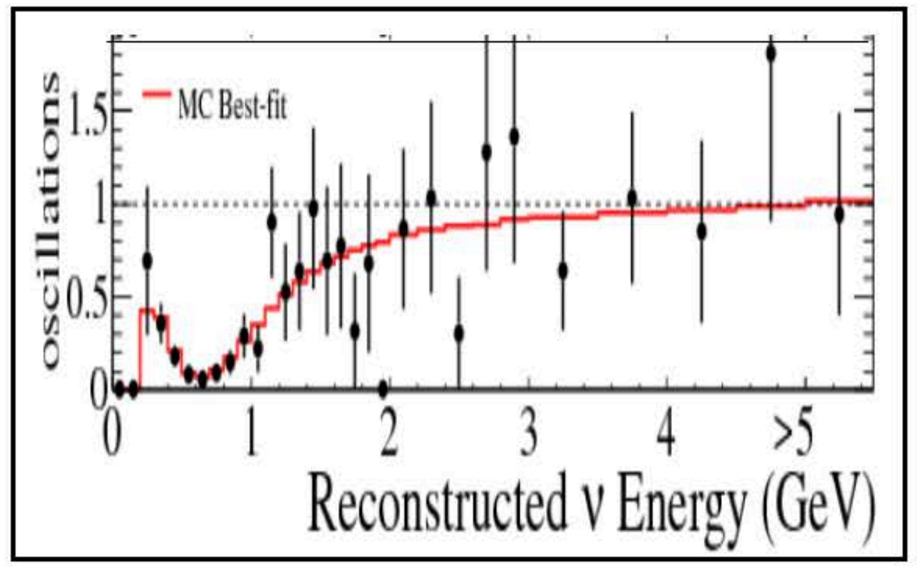
$e \to e$ $(\Delta m^2, \theta_{13})$



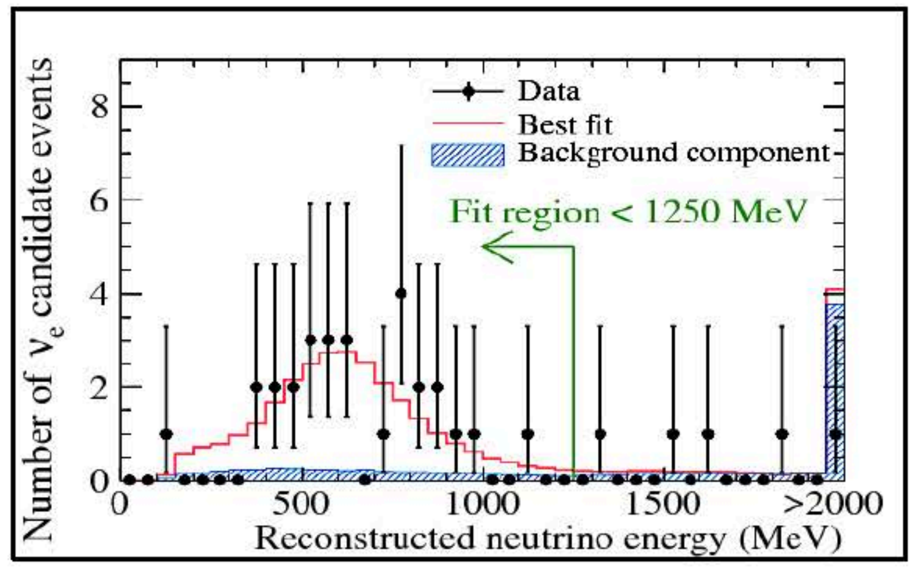
$e \to e$ $(\delta m^2, \theta_{12})$



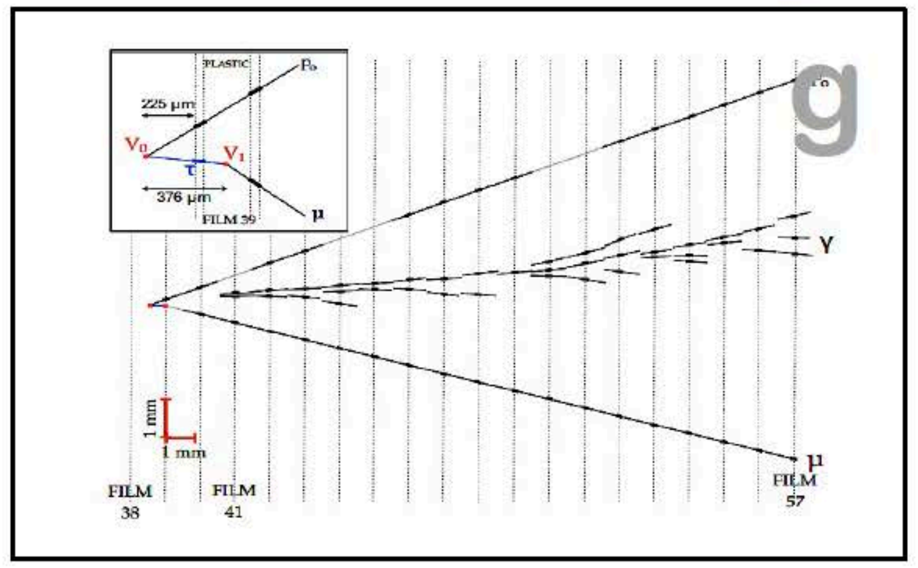
$\mu \to \mu$ $(\Delta m^2, \theta_{23})$



$\mu \to e$ $(\Delta m^2, \theta_{13}, \theta_{23})$



$\mu \to \tau$ $(\Delta m^2, \theta_{23})$



3 flavor picture fits data well

E. Lisi

Neutrino Mixing - 3 Flavor Paradigm

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
	$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
	$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
	$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
	$\delta_{\rm CP}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

$\Delta m^2_{3\ell} \equiv \Delta m^2_{31} > 0$ for NO and $\Delta m^2_{3\ell} \equiv \Delta m^2_{32} < 0$ for IO.

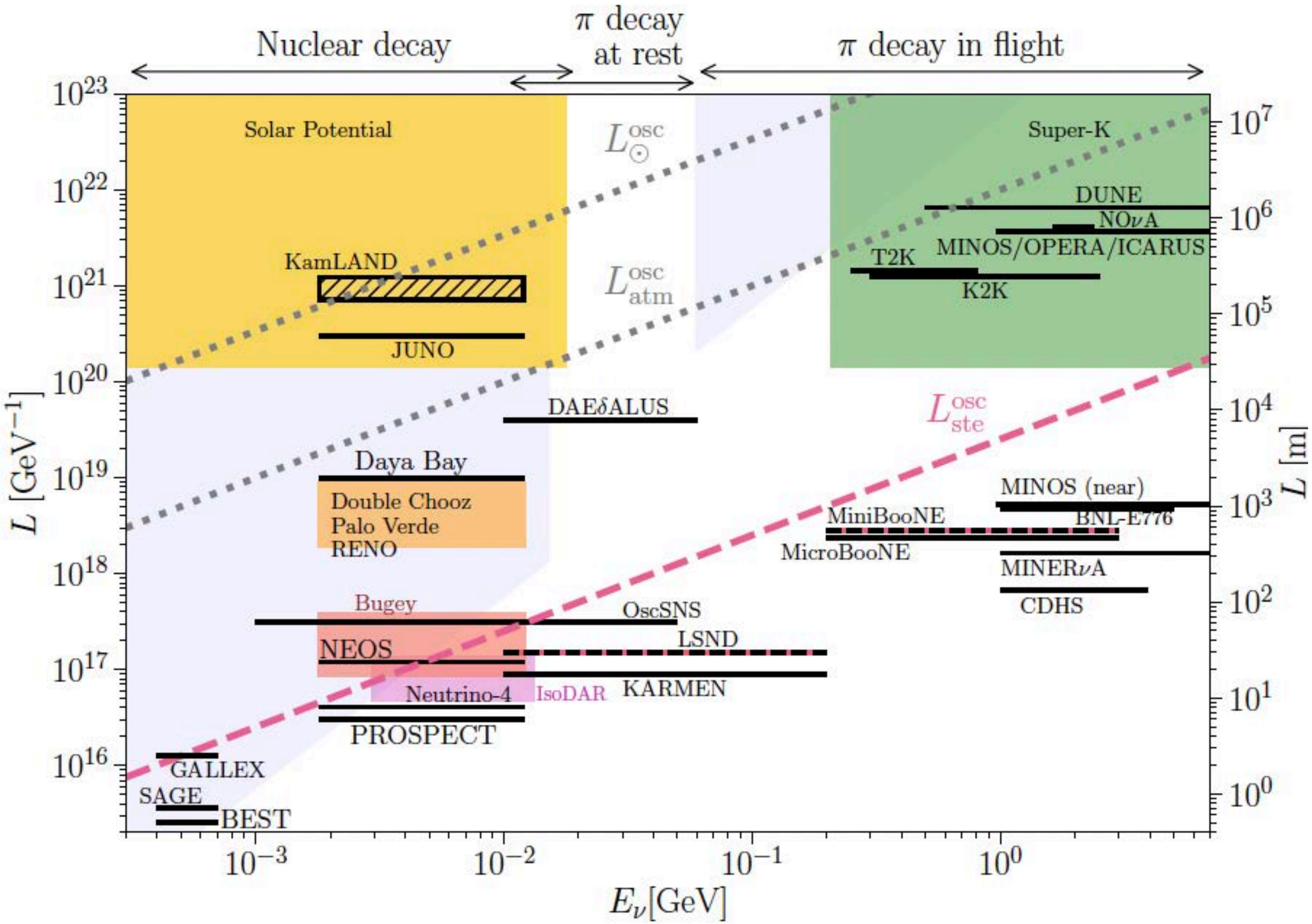
Is θ_{23} non-negligibly greater or smaller than 45 deg?

poor knowledge

sign of Δm^2 unknown (ordering of masses)

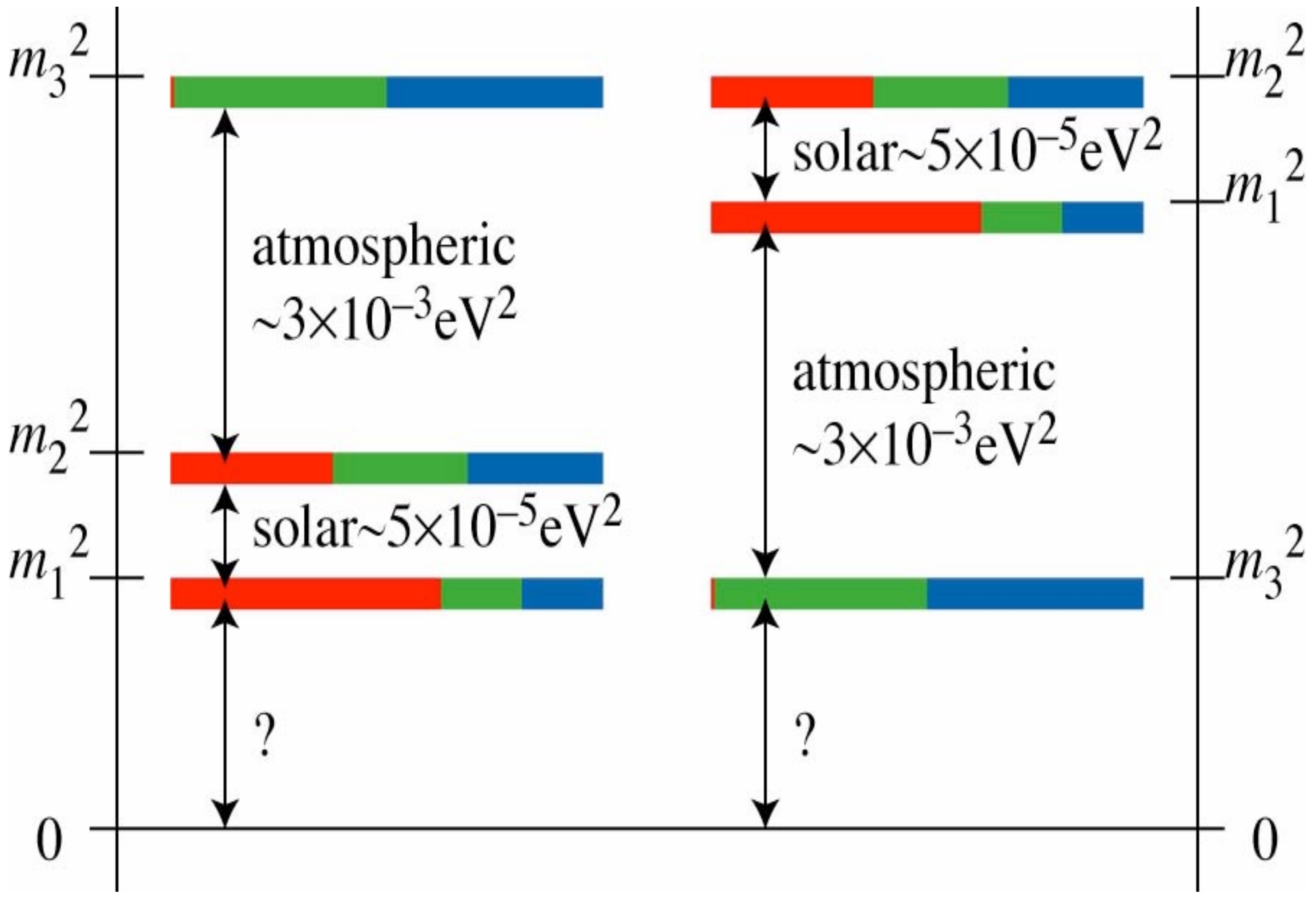
K. Scholberg

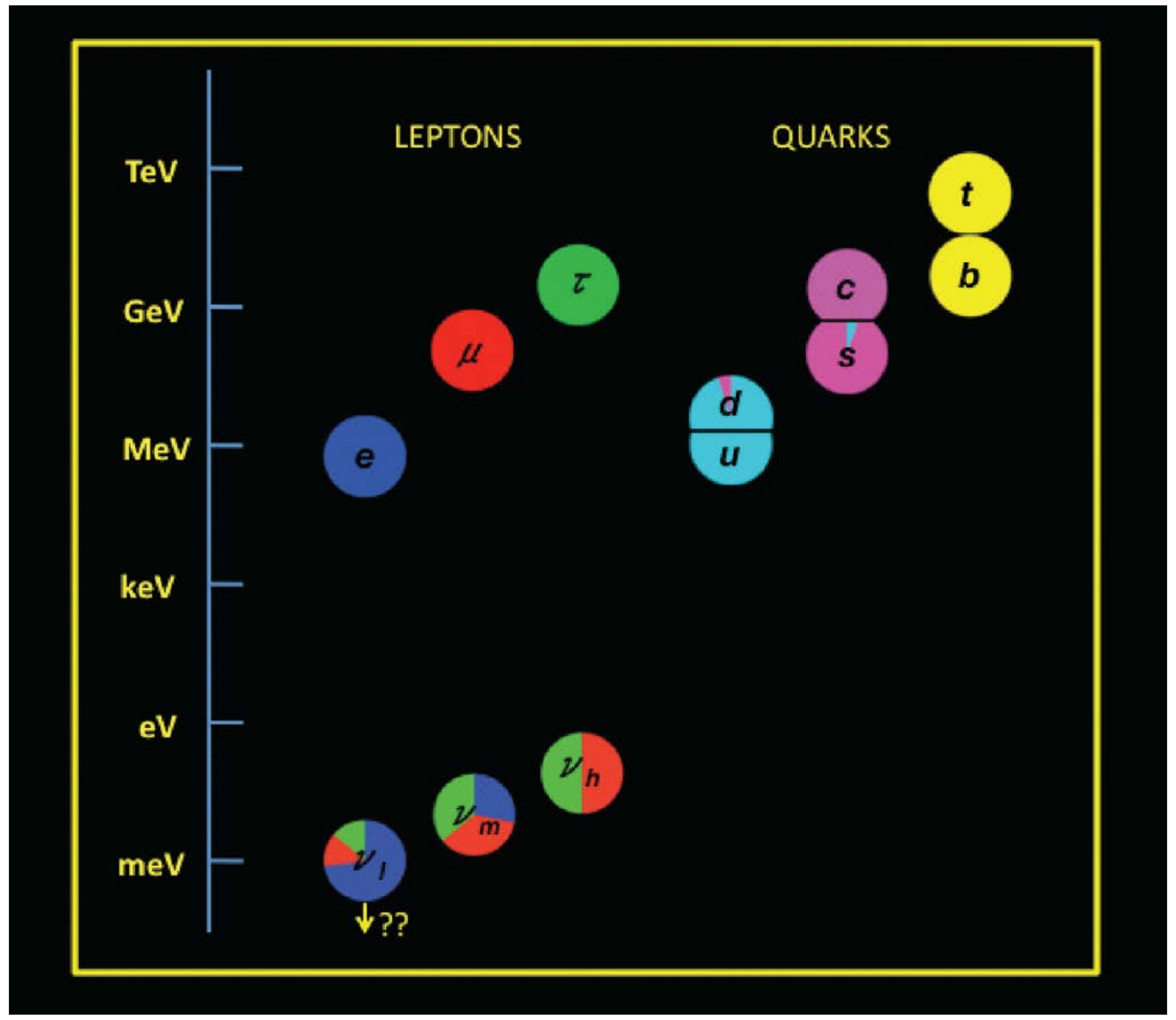
Precision Oscillation Physics



arXiv: 2203.07214

Open Questions

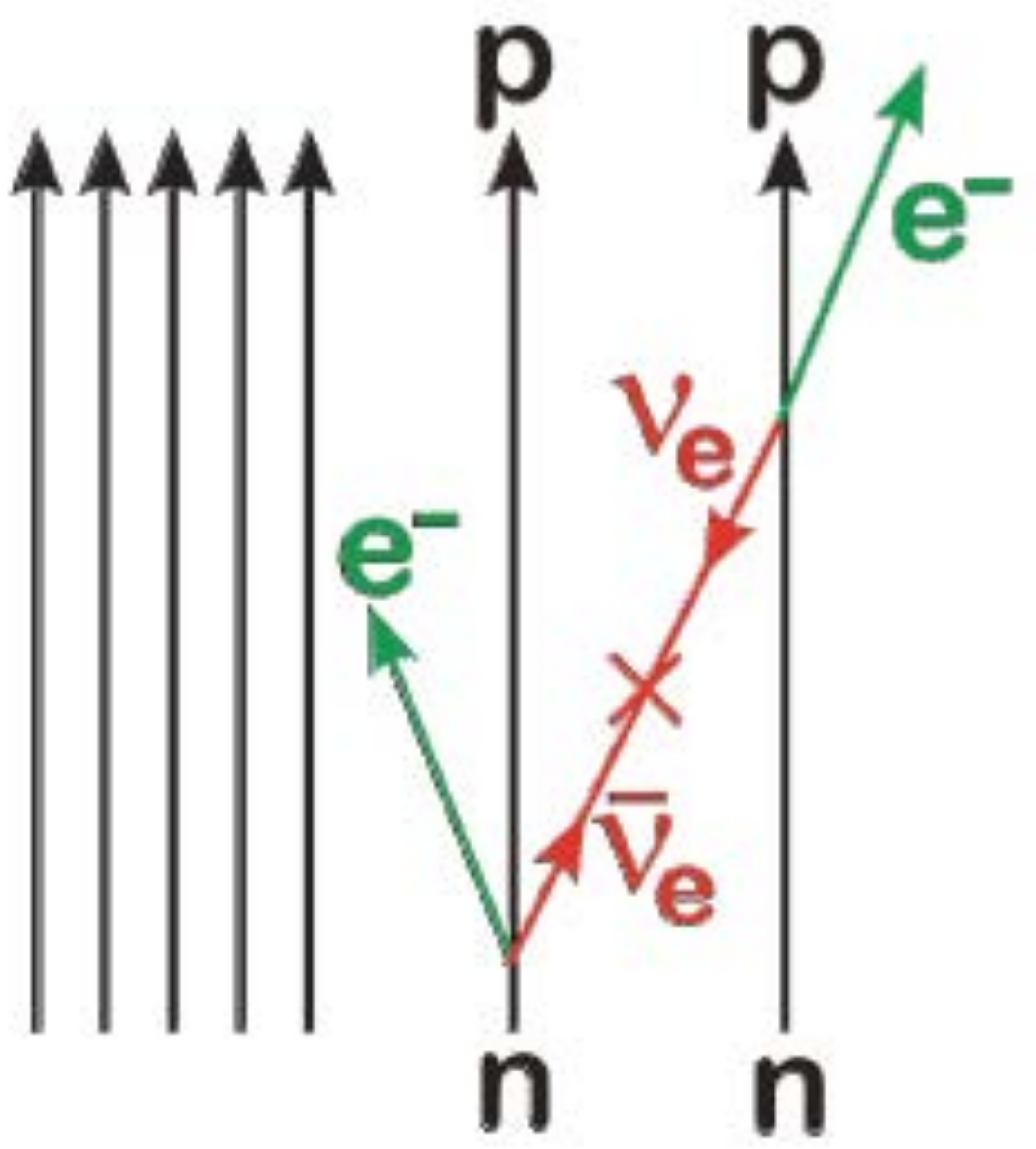


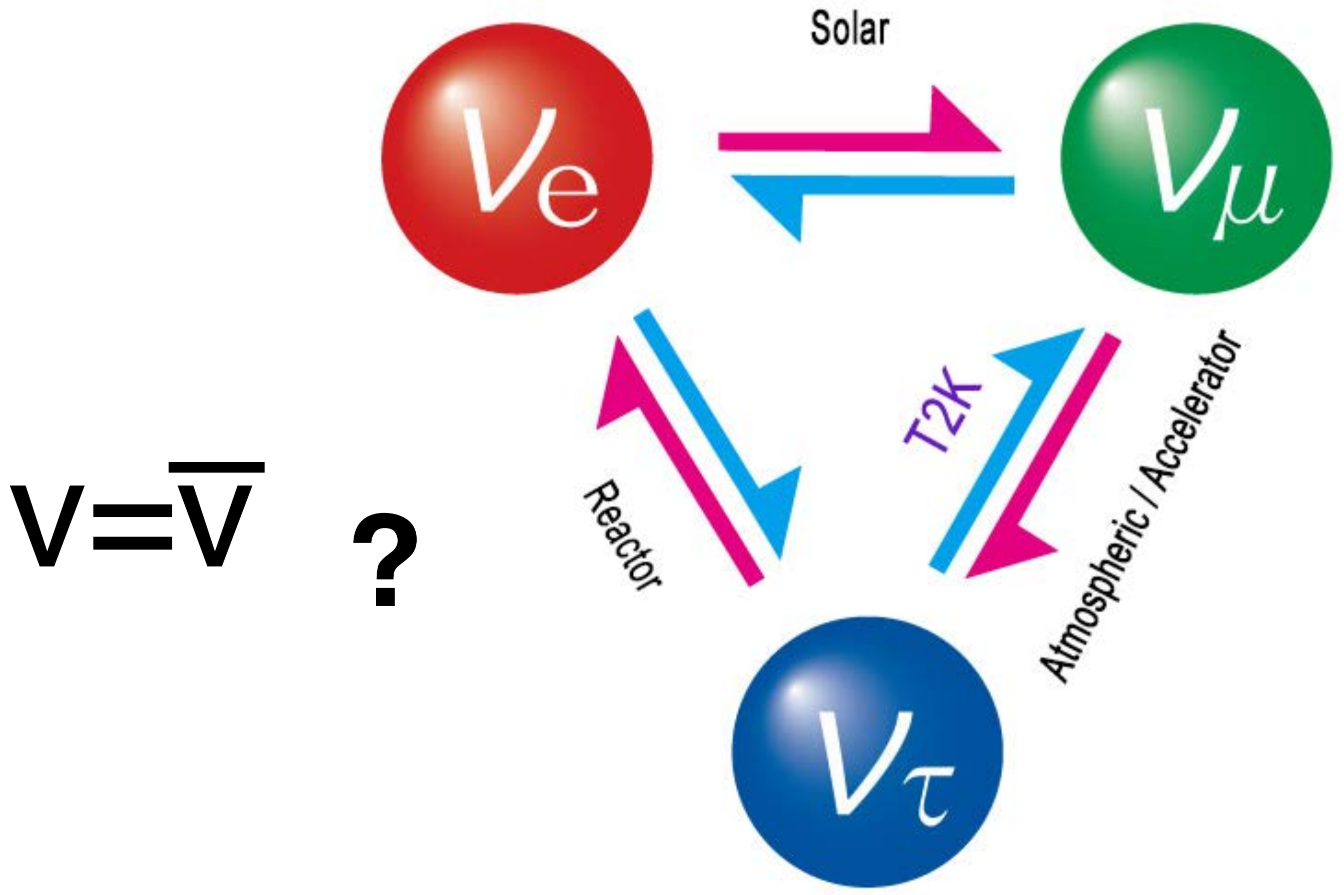


Where do neutrino masses come from?

What is the origin of leptonic mixing?

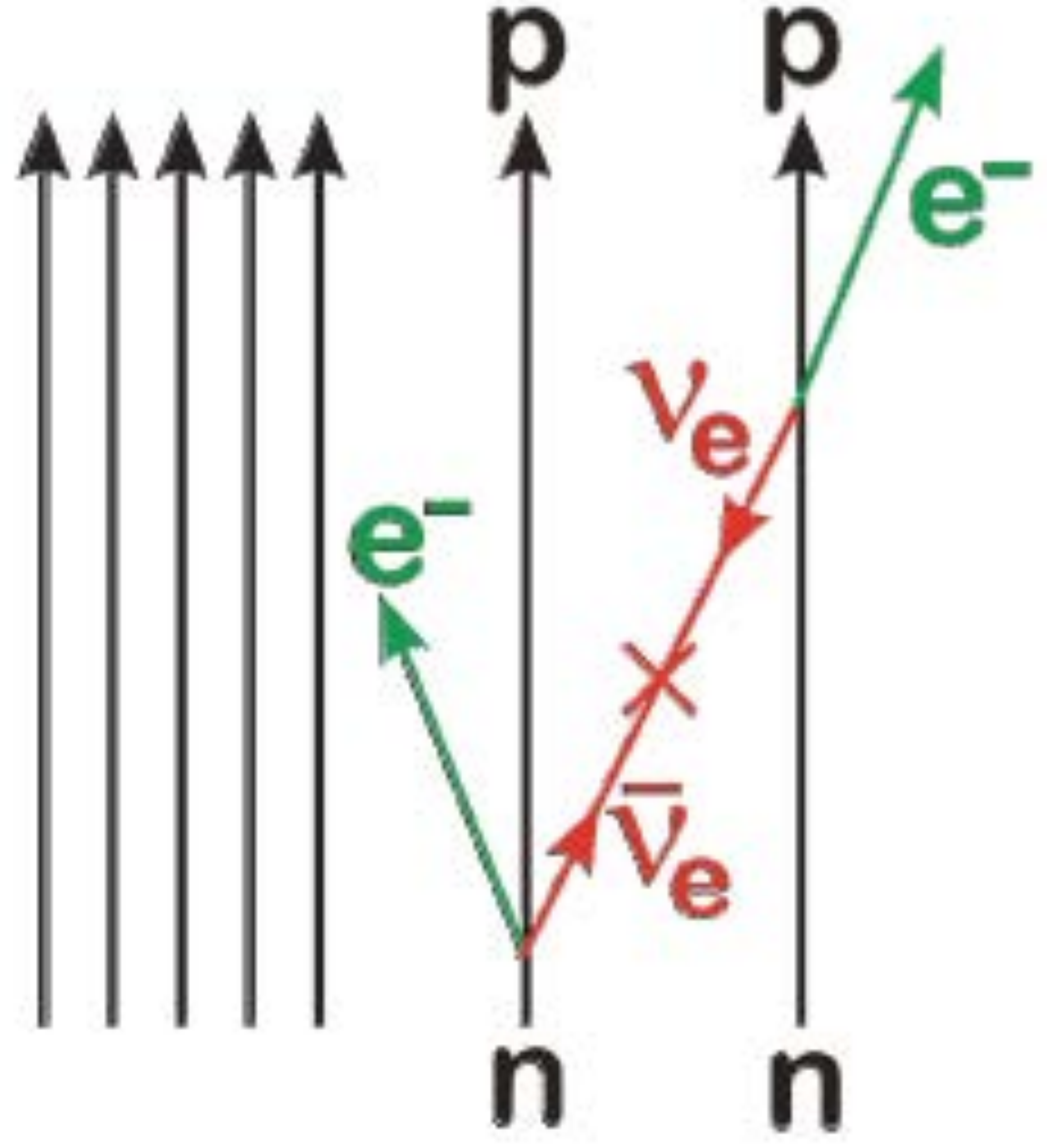
Are neutrinos their own antiparticles?





Major discoveries ahead

What is the nature of neutrino mass?

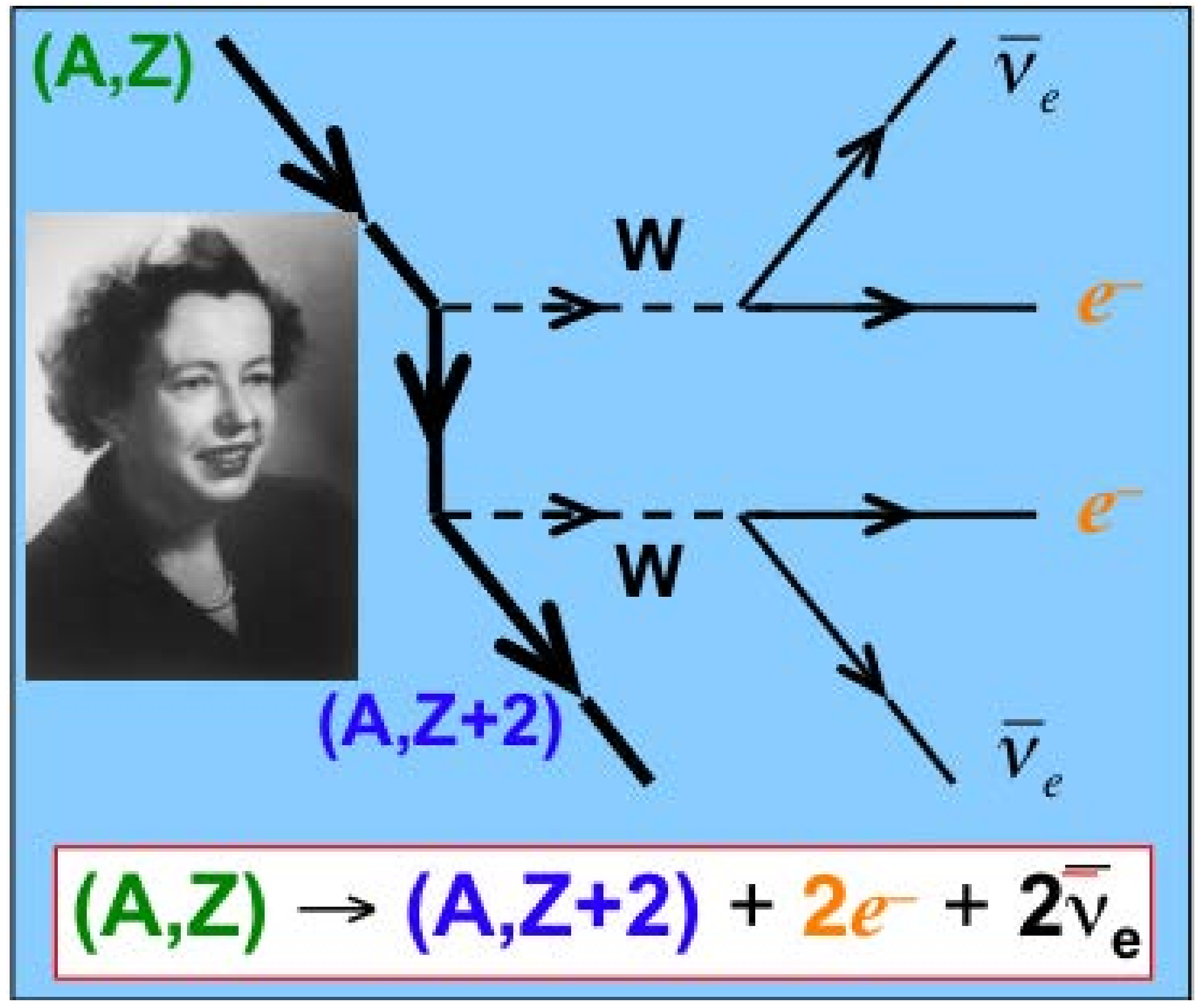


$\nu = \bar{\nu}$?

Understanding Neutrino Mass from Double Beta Decay

Nuclei as a laboratory to study lepton number violation at low energies

$2\nu\beta\beta$



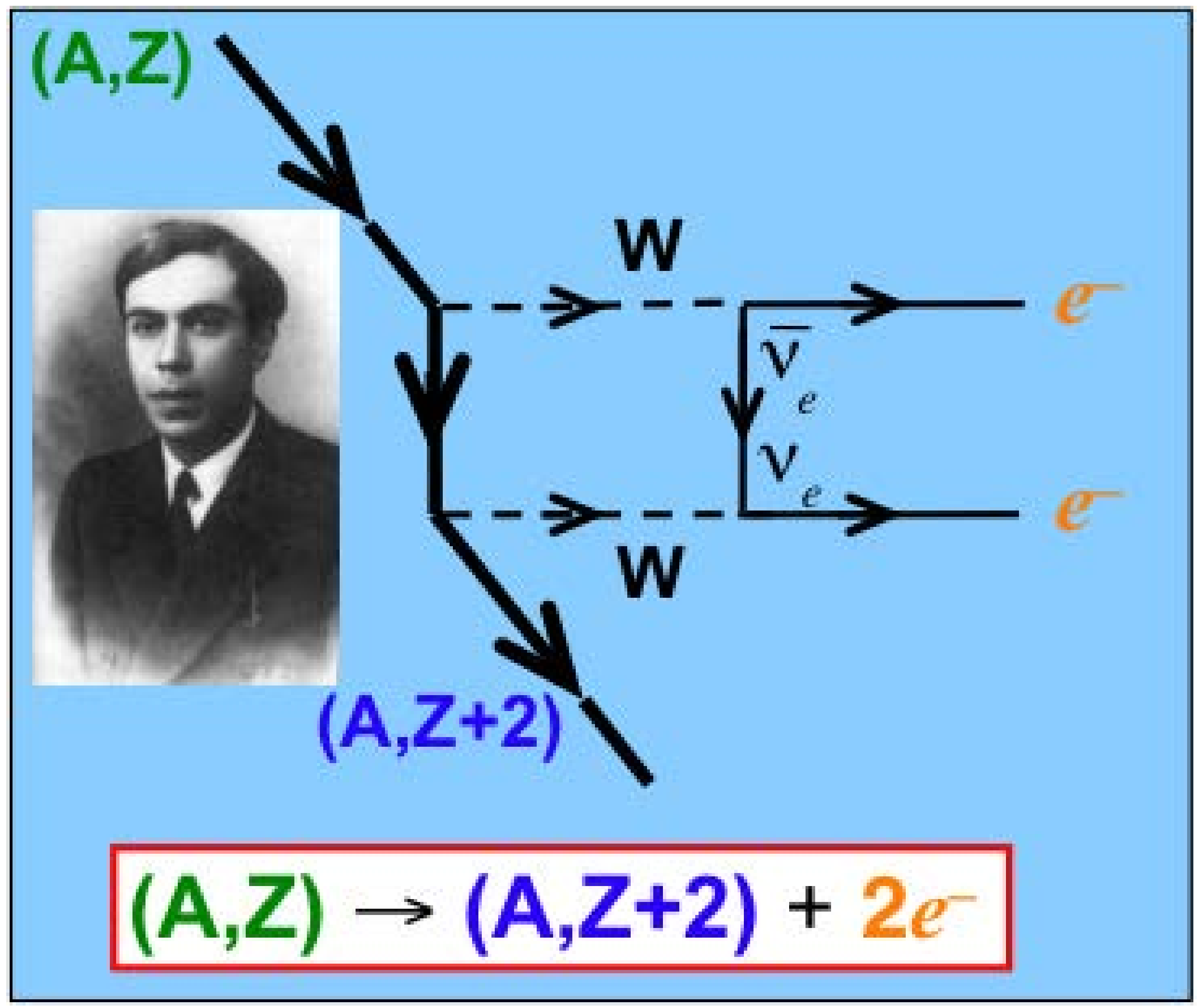
Proposed in 1935 by Maria Goeppert-Mayer

Observed in several nuclei

$T_{1/2} \sim 10^{19} – 10^{21}$ yrs

$$\Gamma_{2\nu} = G_{2\nu} \mid M_{2\nu} \mid^2$$

$0\nu\beta\beta$



Proposed in 1937 by Ettore Majorana

Not observed yet

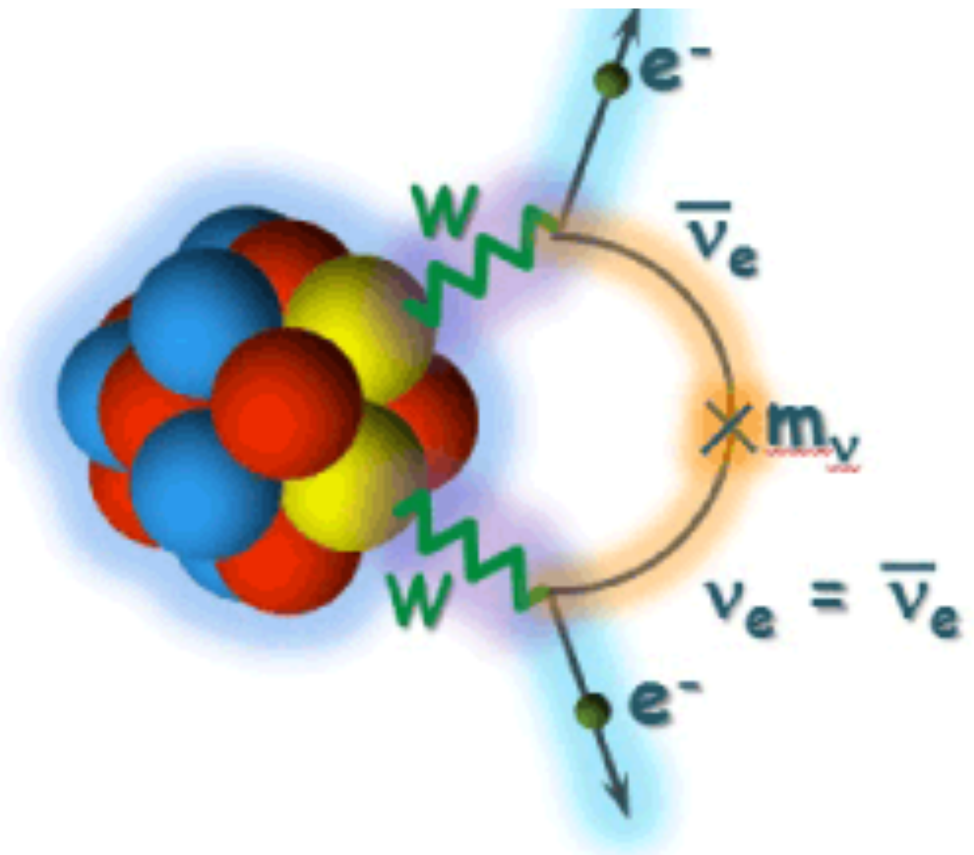
$T_{1/2} \geq 10^{25}$ y

$$\Gamma_{0\nu} = G_{0\nu} \mid M_{0\nu} \mid^2 \left\langle m_{\beta\beta} \right\rangle^2$$

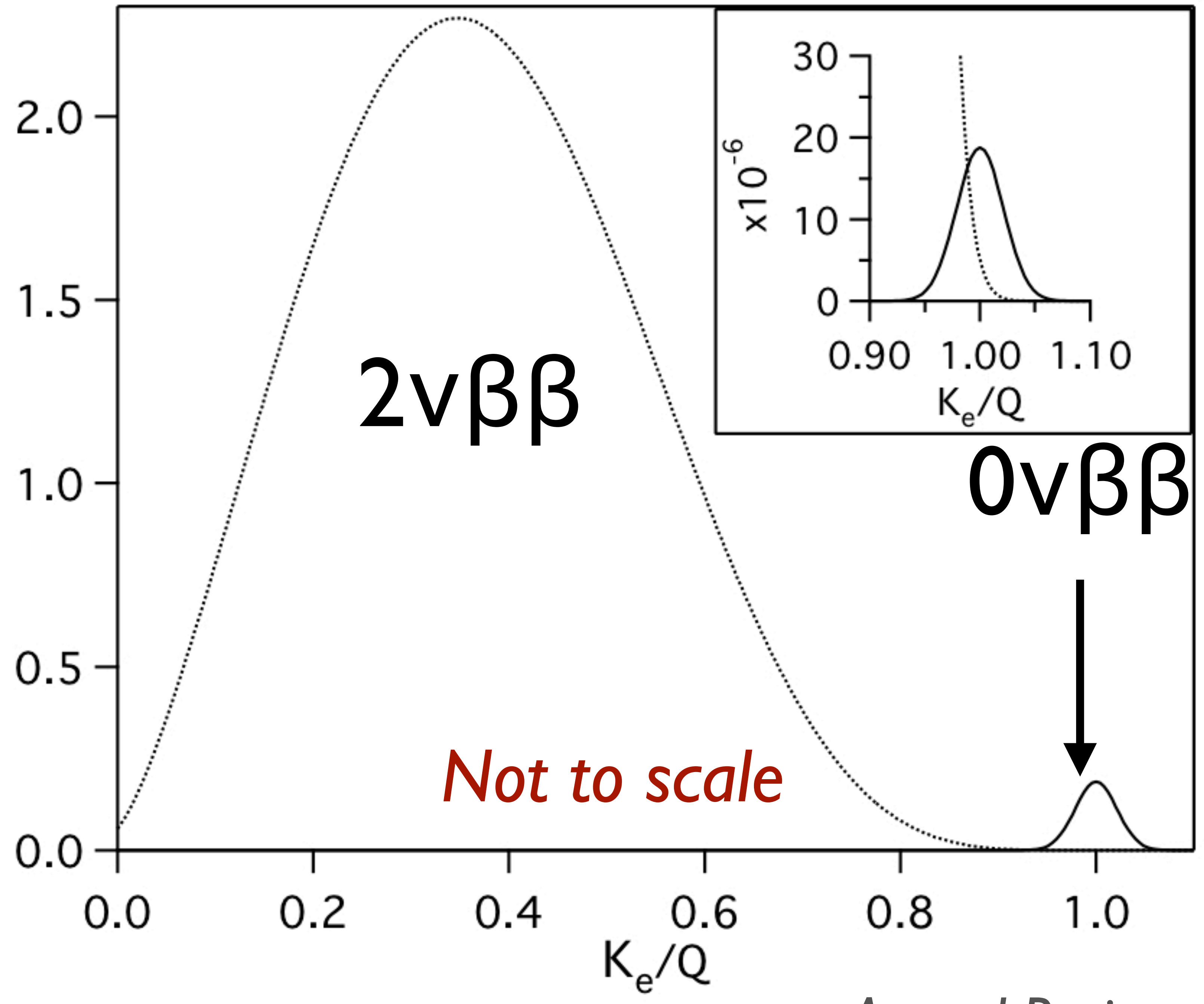
$0\nu\beta\beta$ would imply

- lepton number non-conservation
- Majorana nature of neutrinos

Neutrinoless Double Beta Decay (0νββ)



Neutrinoless double beta decay



Annual Reviews: 52:115-151

Sensitivity

Mass

Runtime

Efficiency

$$S_{0\nu} \quad \propto \quad a\,\varepsilon \sqrt{\frac{M\,t}{B\,\Delta E}}$$

Isotopic abundance

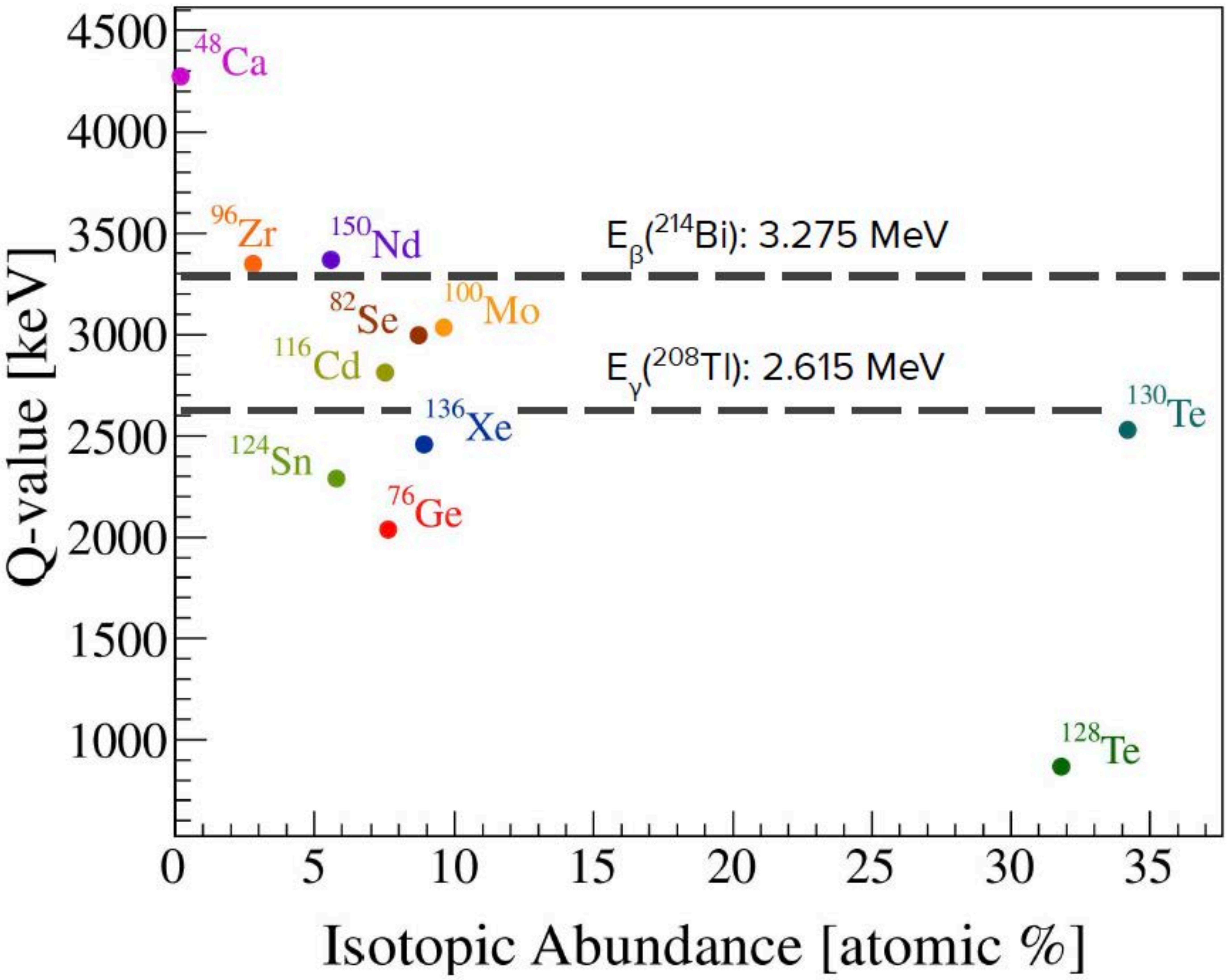
Background

Energy resolution

Search for peak search at the Q value of the decay

Energy peak is necessary and sufficient signature to claim a discovery.
Additional signatures from signal topology etc

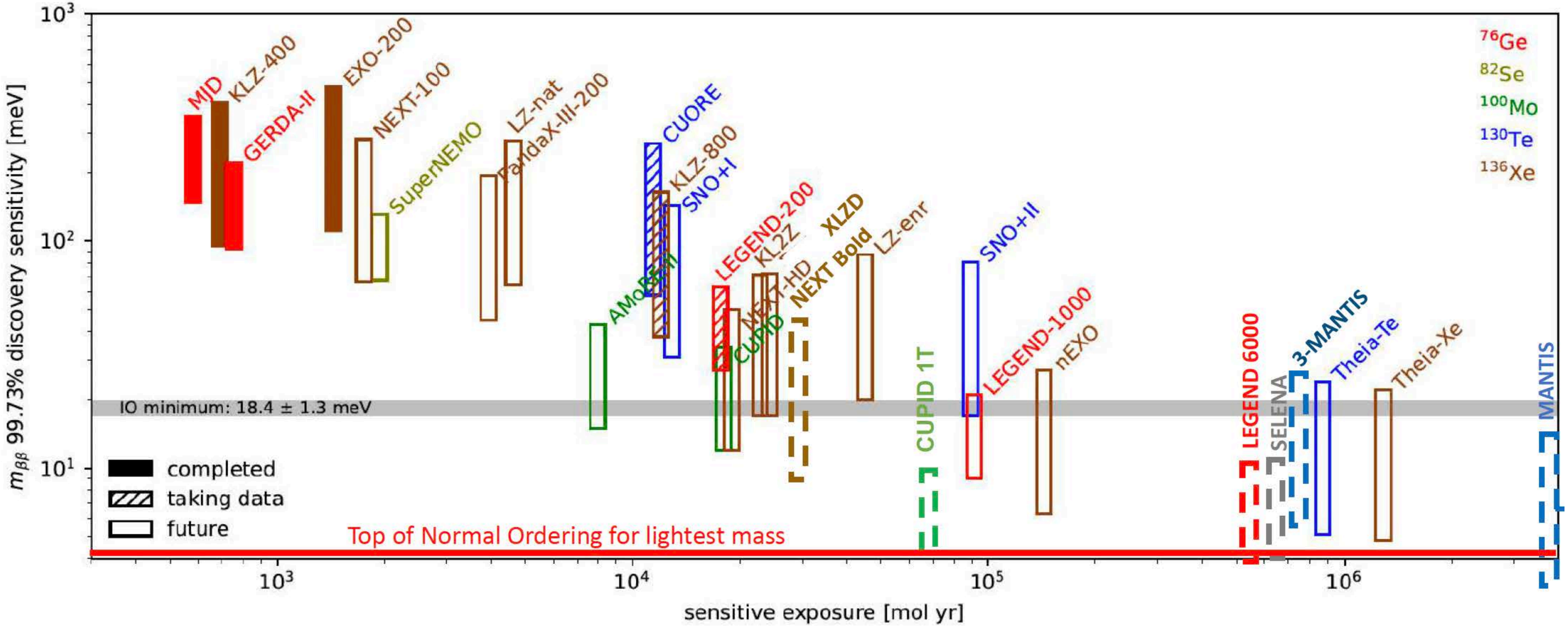
Isotope Choice



Desired Characteristics

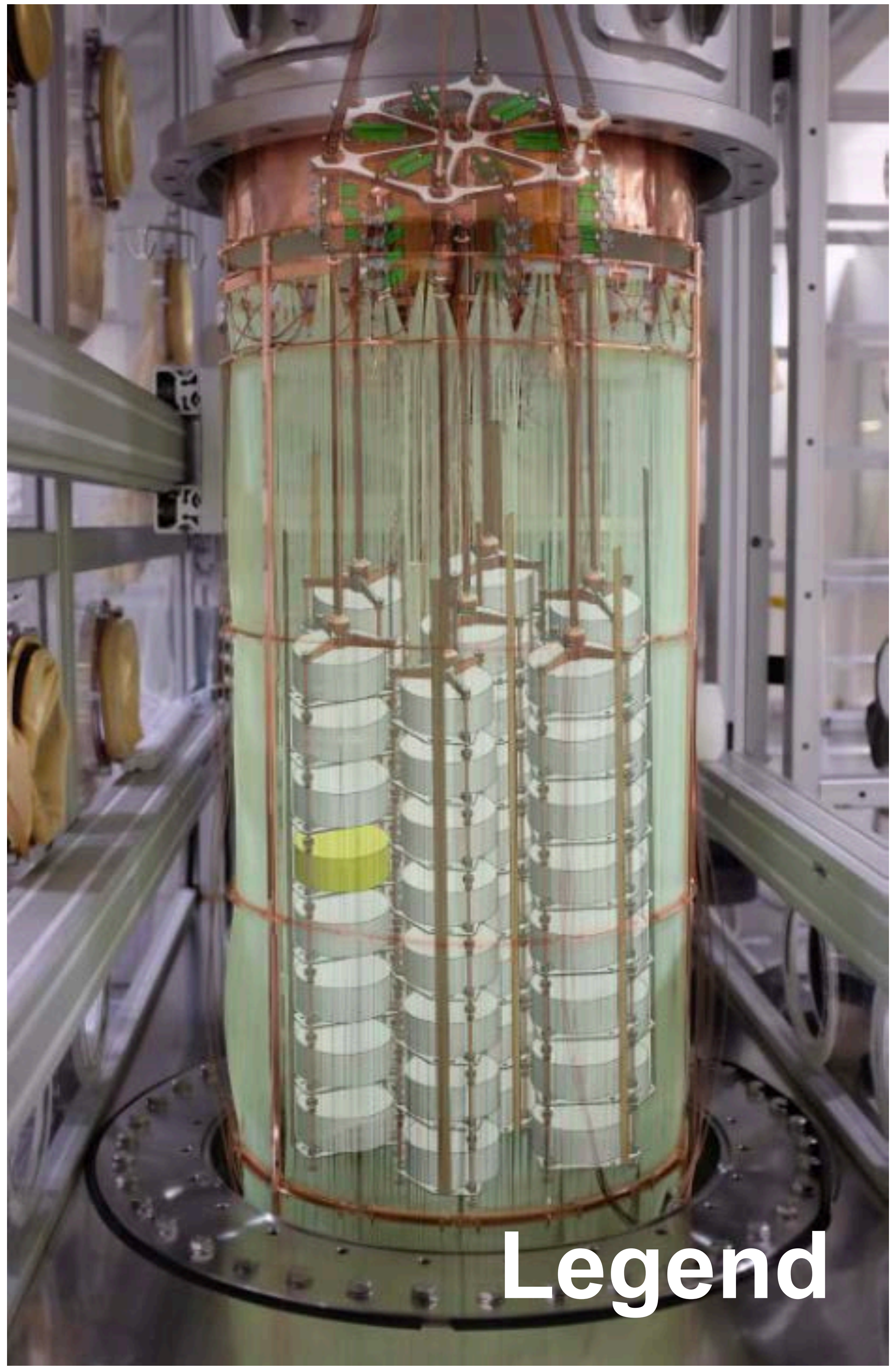
- High isotopic abundance
- Enrichment possible
- Qββ above end point of β or γ radiation
- Large scale production possible

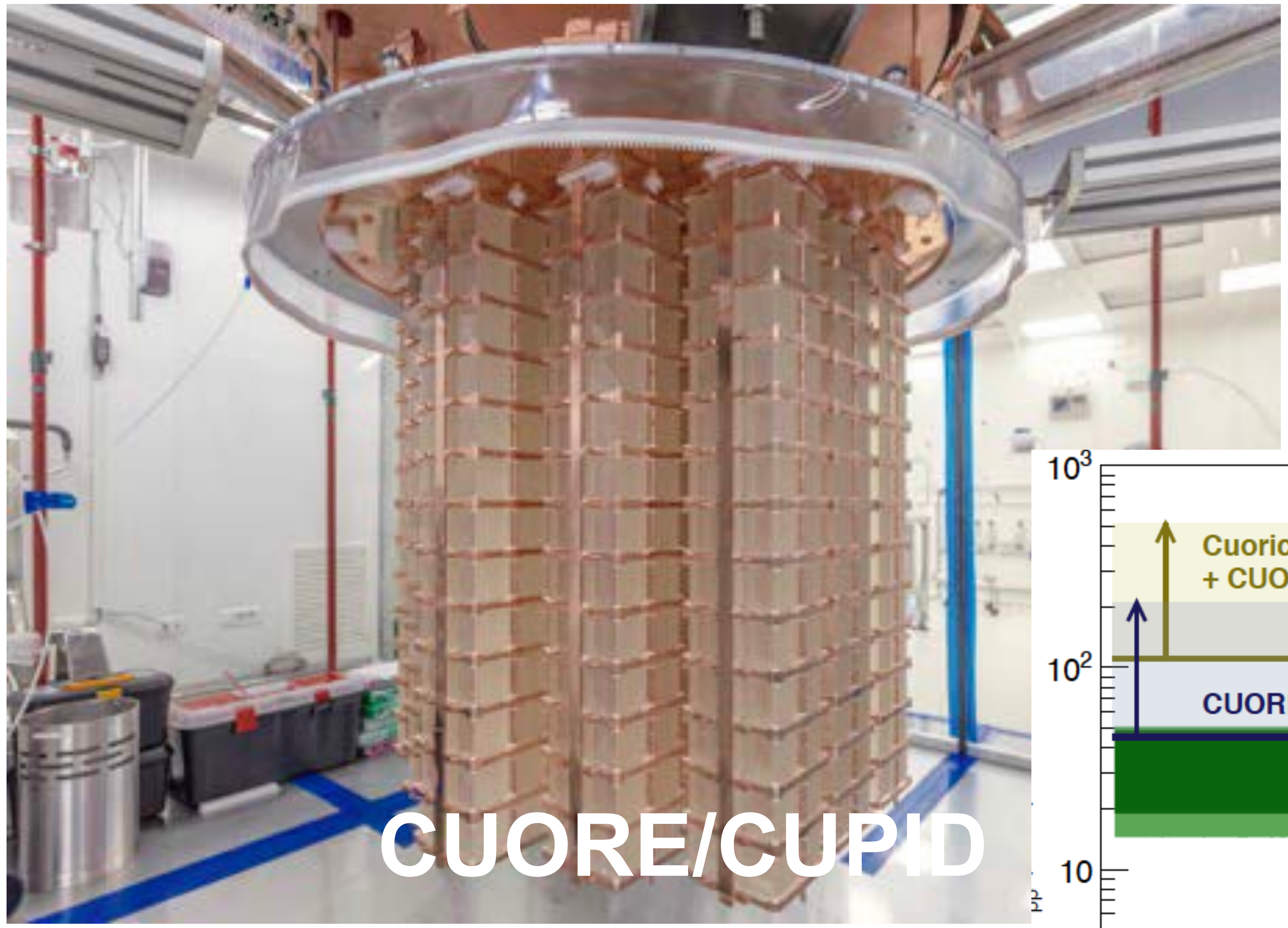
Isotope Choice

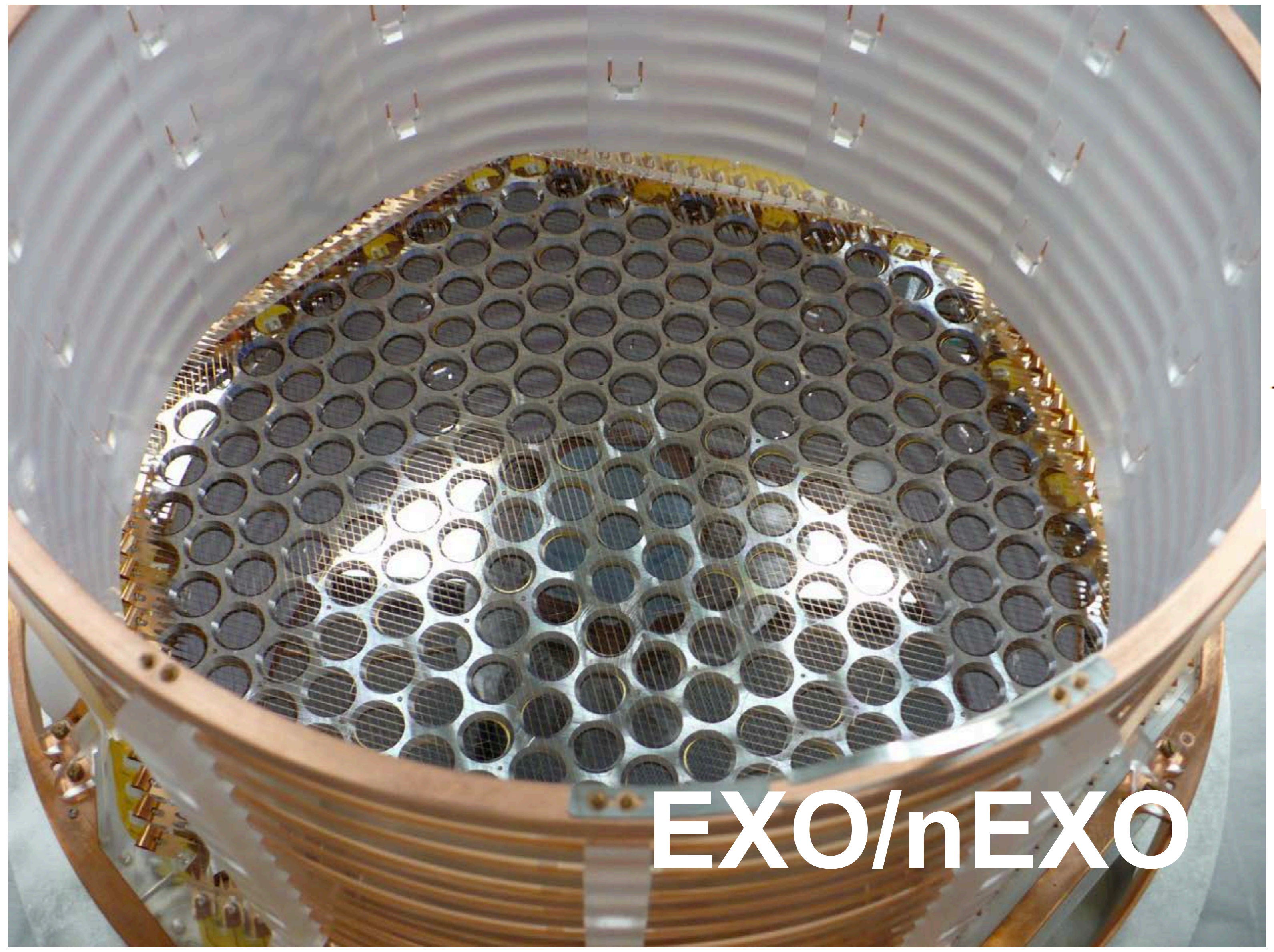


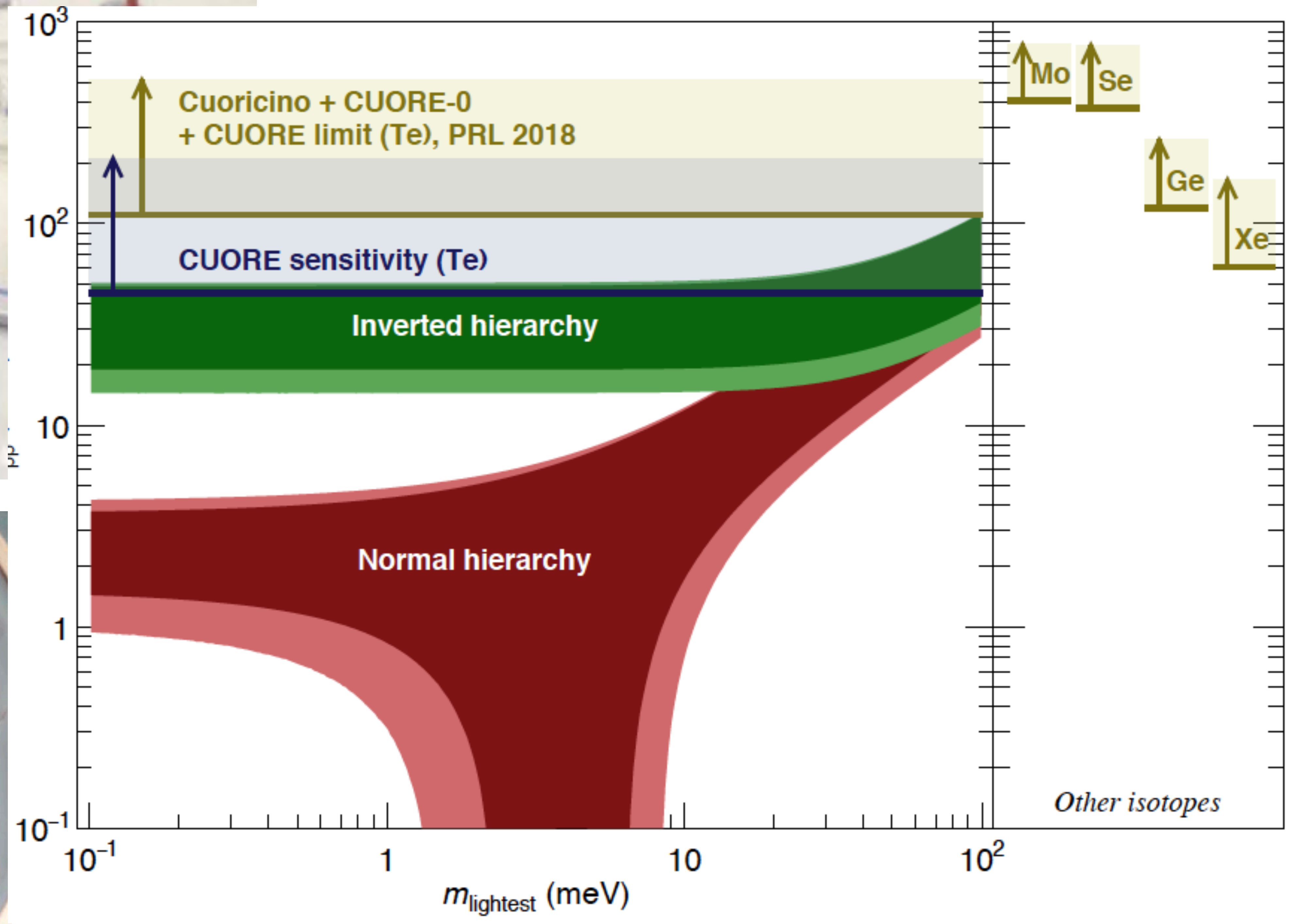
From: Fundamental Symmetries, Neutrons, and Neutrinos (FSNN): Whitepaper for the 2023 Nuclear Science Advisory Committee Long Range Plan: arXiv:2304.03451iv:2304.03451

0νββ Searches









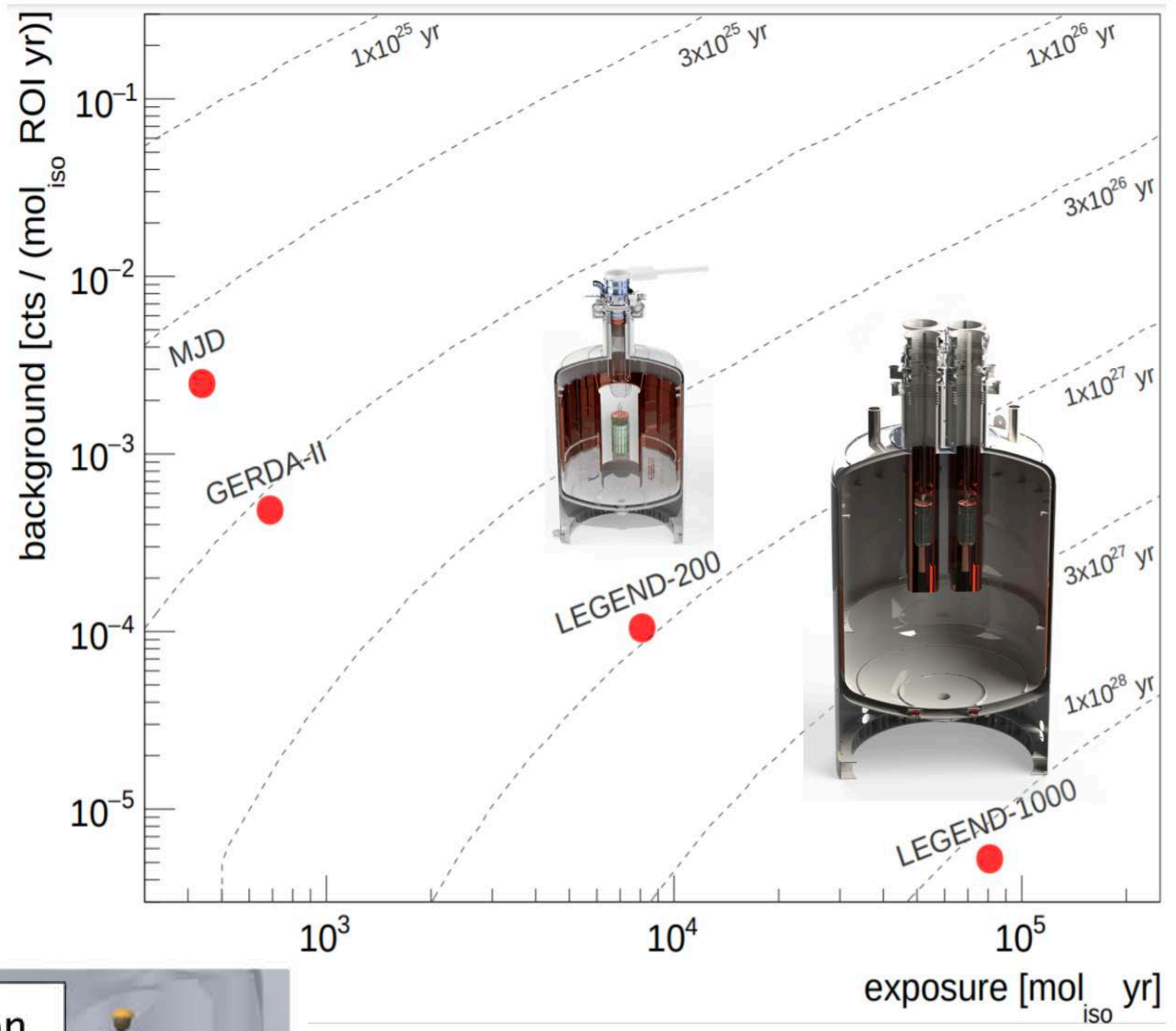
pushing limits towards inverted hierarchy

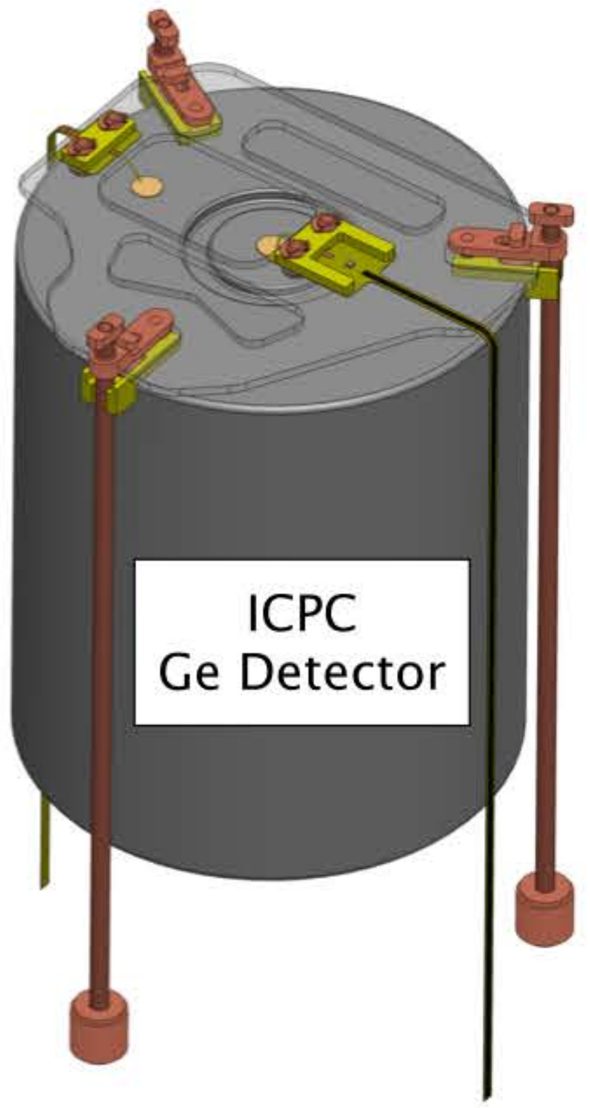
LEGEND

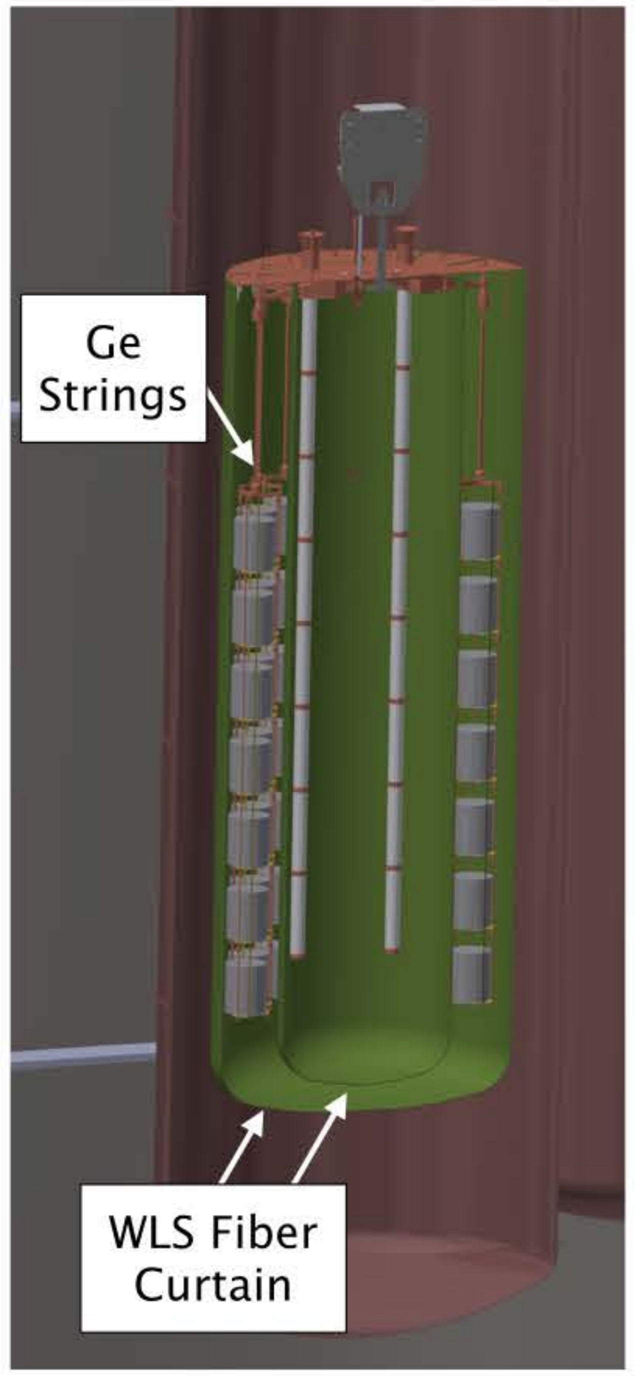
1000 kg of enriched Ge detectors (enriched to 92% ^{76}Ge)

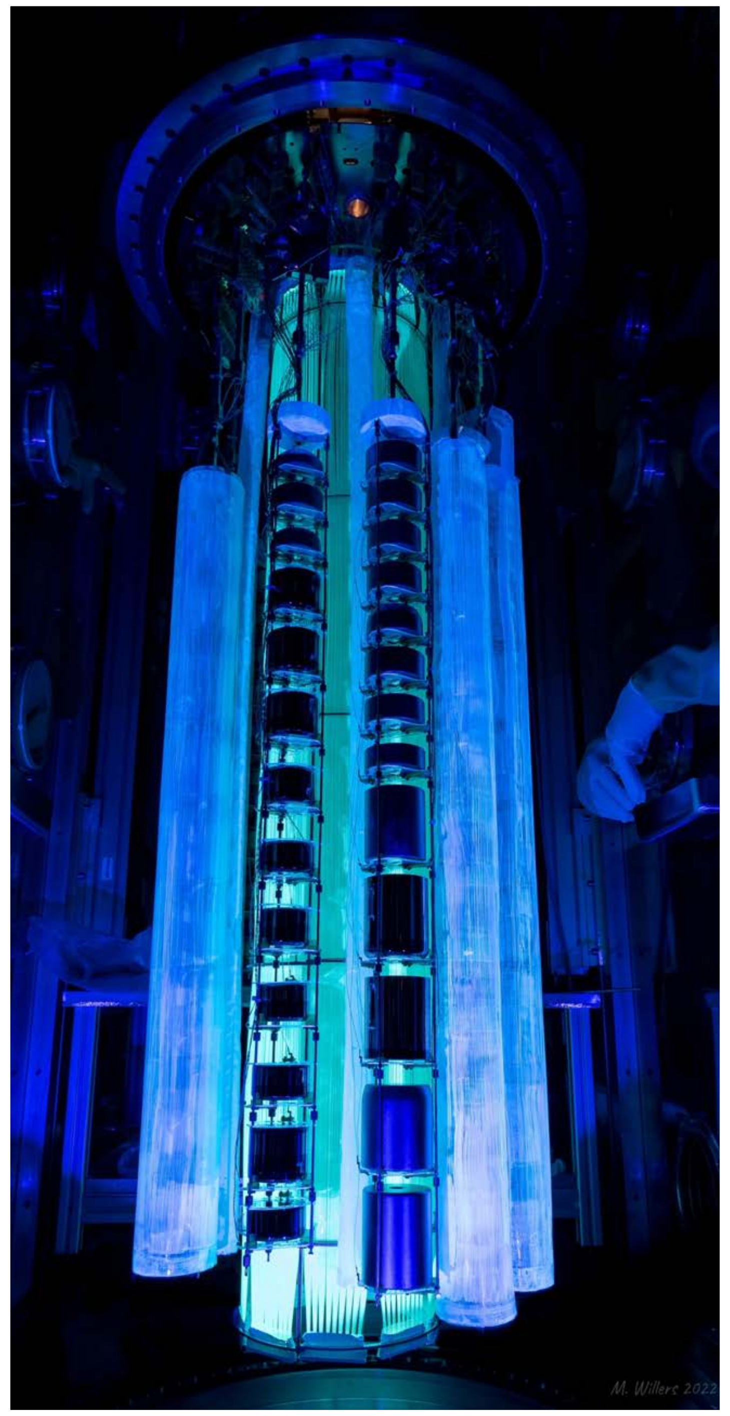
- 2.6 kg average mass
- Mounted in "strings" using components made from electroformed copper and scintillating plastic, PEN
- ASIC readout front-end electronics

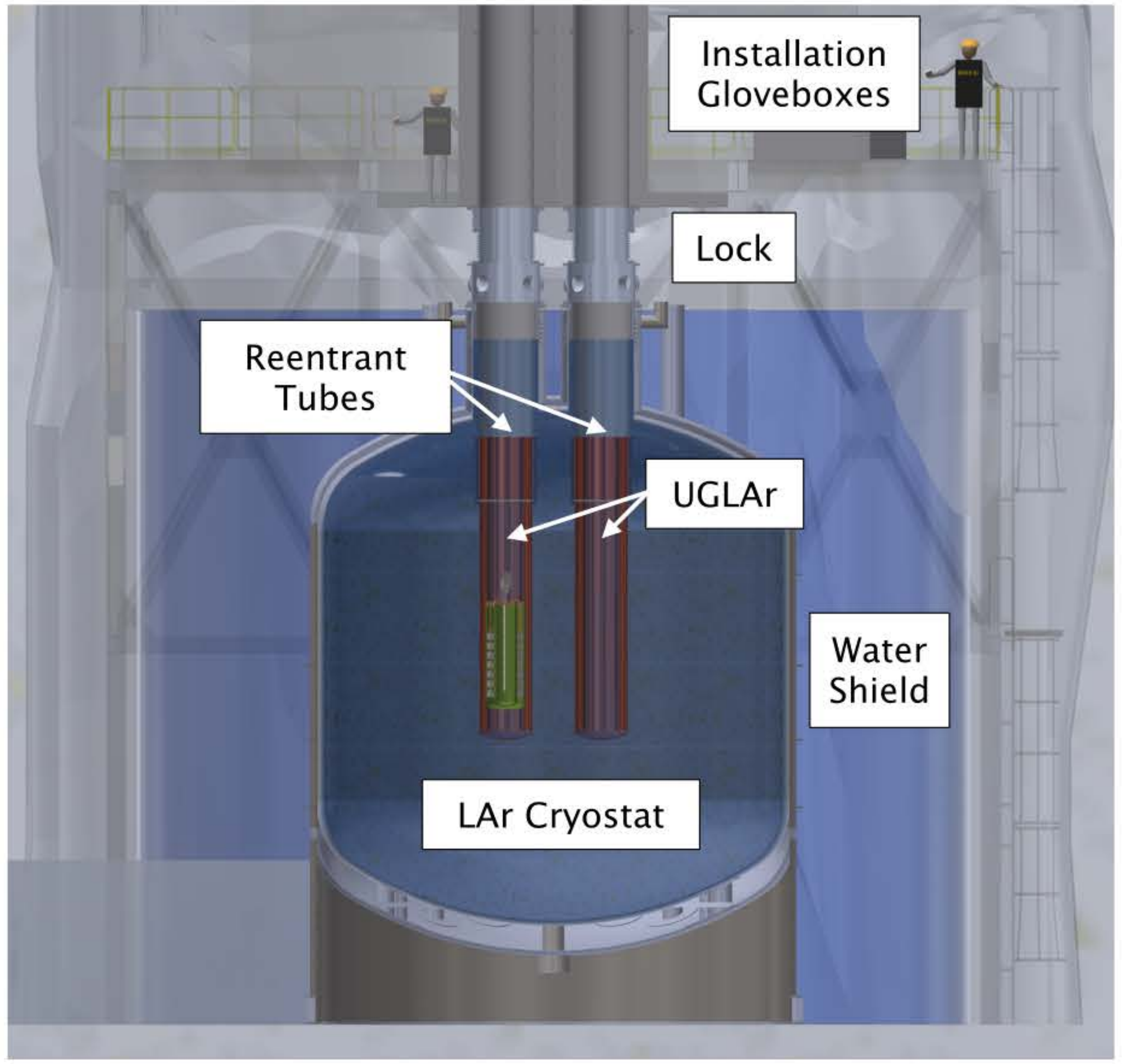
- Underground-sourced LAr active shield
- Dual fiber-curtain LAr instrumentation
- EFCu Reentrant tubes









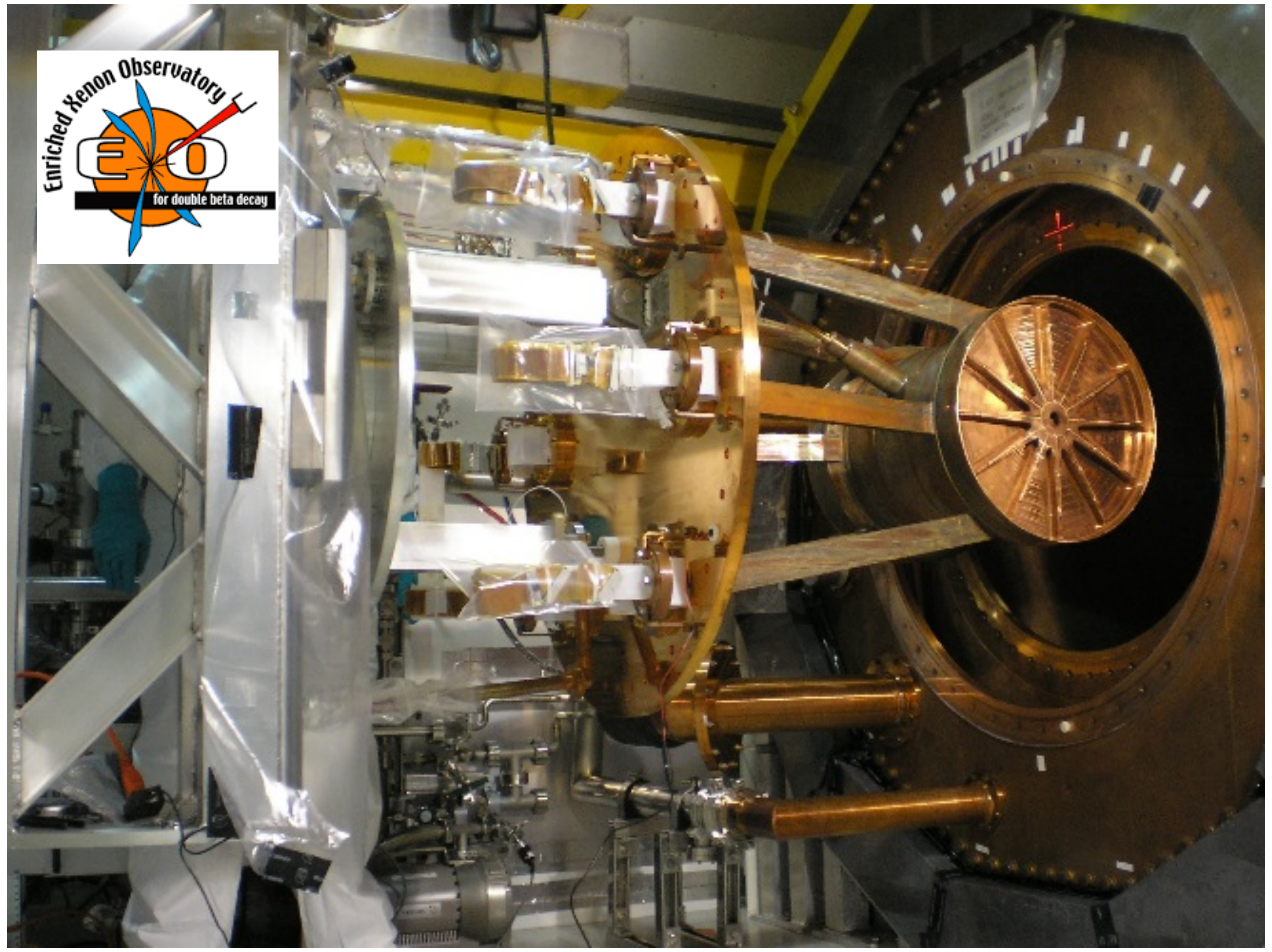


EXO

EXO-200 at WIPP (Decommissioned in Dec. 2018):

- EXO-200 first 100-kg class ββ experiment
- 175 kg liquid-Xe TPC with ~80% Xe-136
- Discovered 2νββ in Xe-136
- Demonstrated excellent background identification through multiplicity and location of event in TPC

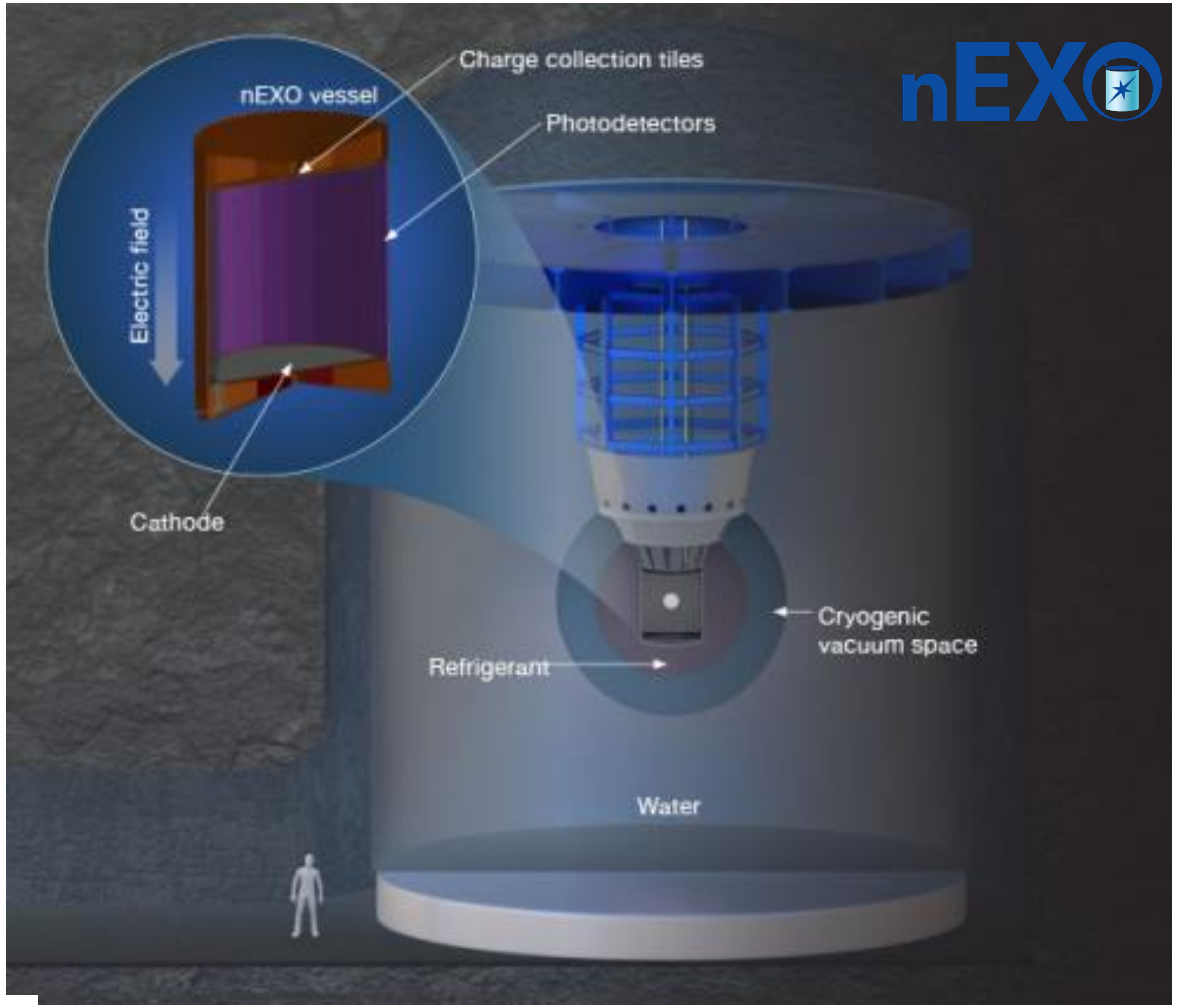
  → this is essential for nEXO design



https://www-project.slac.stanford.edu/exo/

nEXO:

- 5-tonne liquid Xe TPC
- Enriched in Xe-136 at ~90%
- SNOLAB cryopit preferred location by collaboration

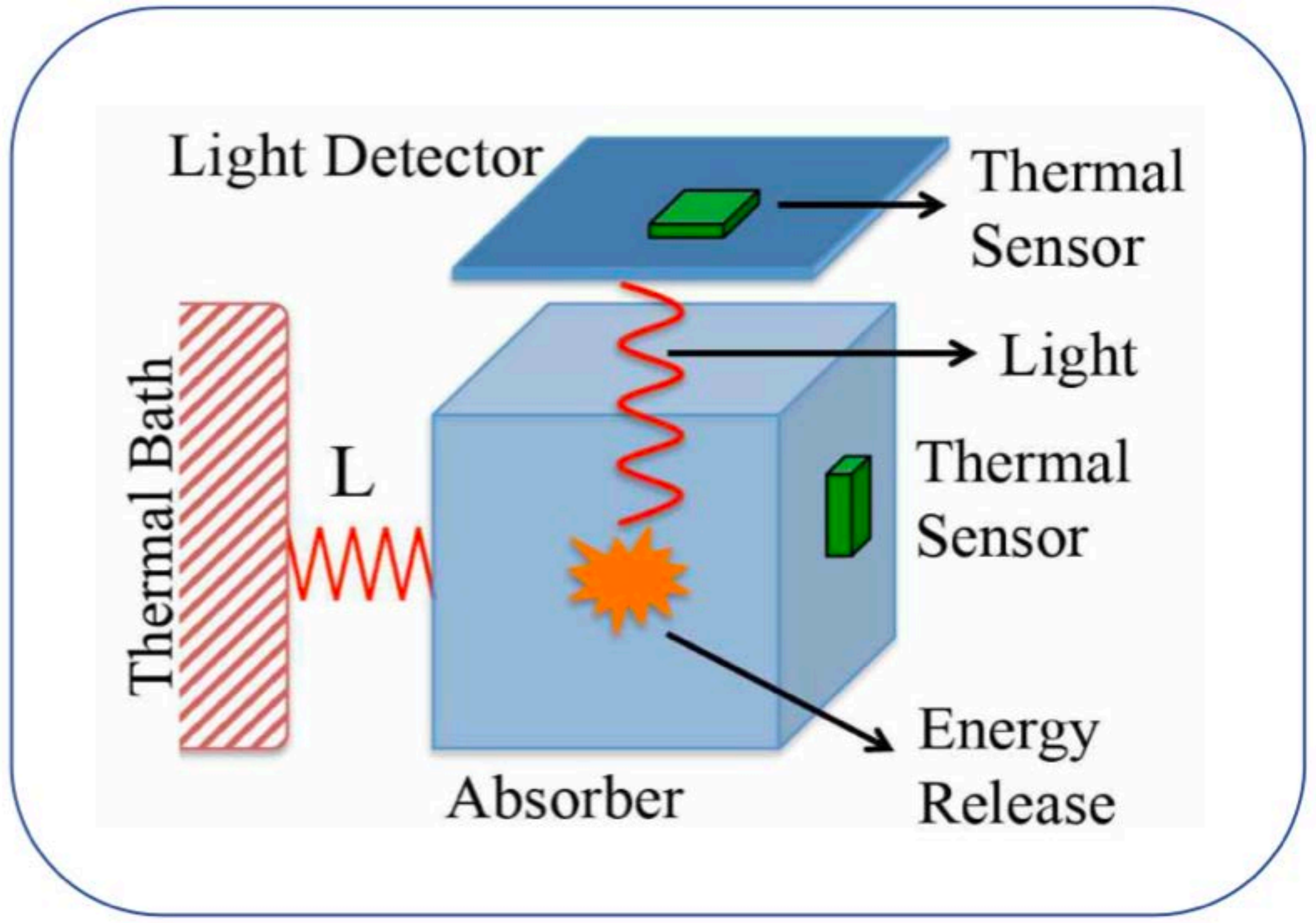


https://nexo.llnl.gov/

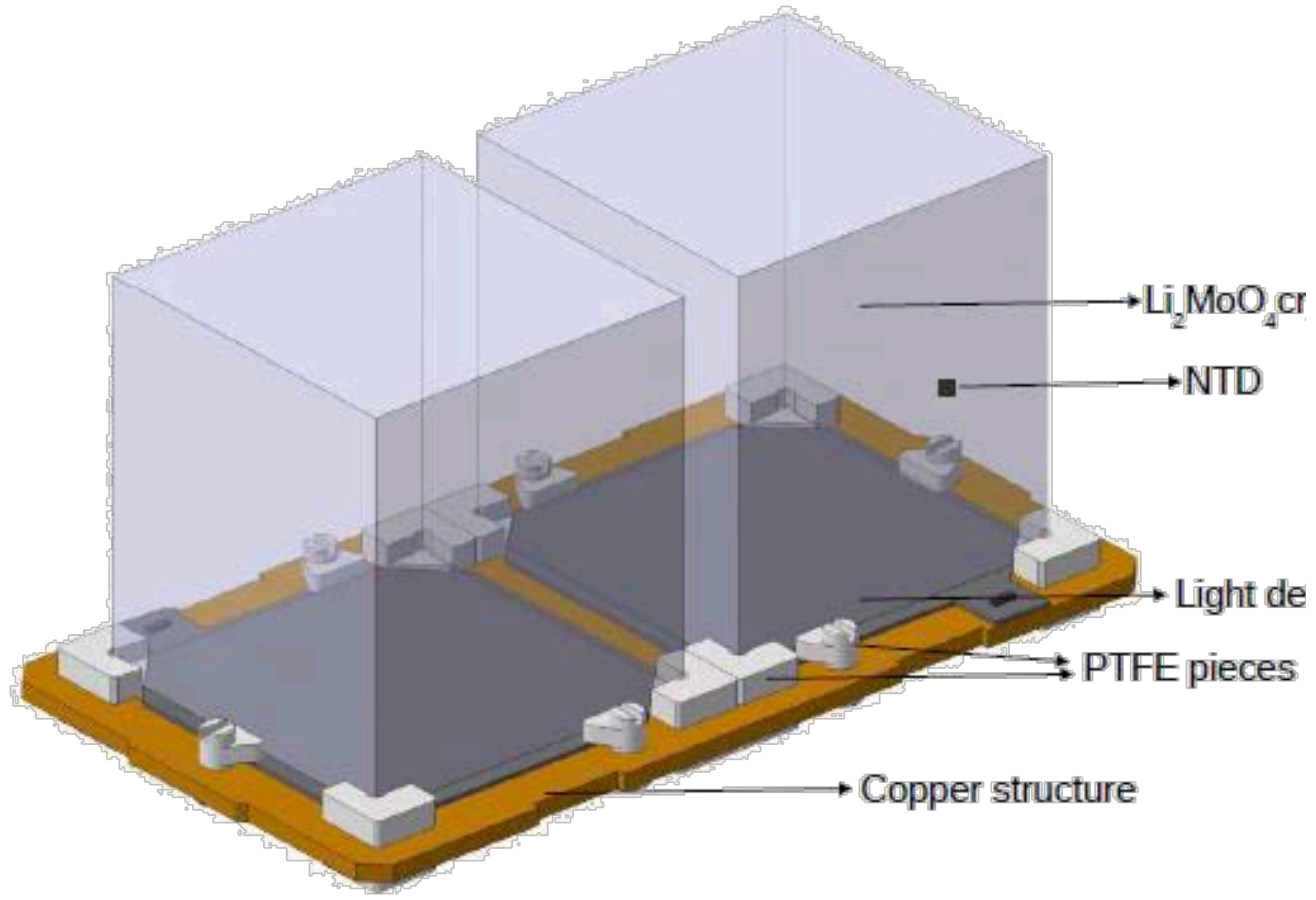
CUPID: CUORE Upgrade with Particle Identification

Single module: $Li_2{}^{100}MoO_4$, 45x45x45 mm, 280 g
Detector: 57 towers of 14 floors with 2 crystals each, 1596 crystals
~240 kg of ^{100}Mo with >95% enrichment
~1.6×10^{27} ^{100}Mo atoms
Ge light detector as in CUPID-Mo, CUPID-0

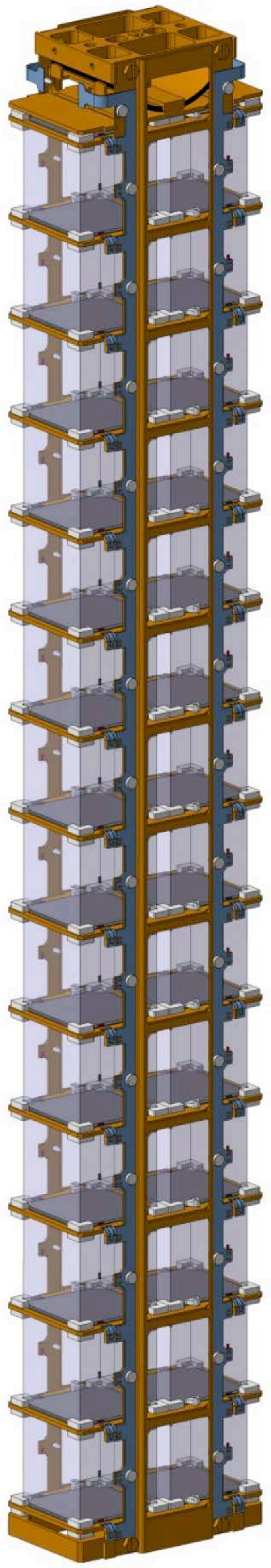
CUPID ^{100}Mo
heat + light
(scintillating bolometer)

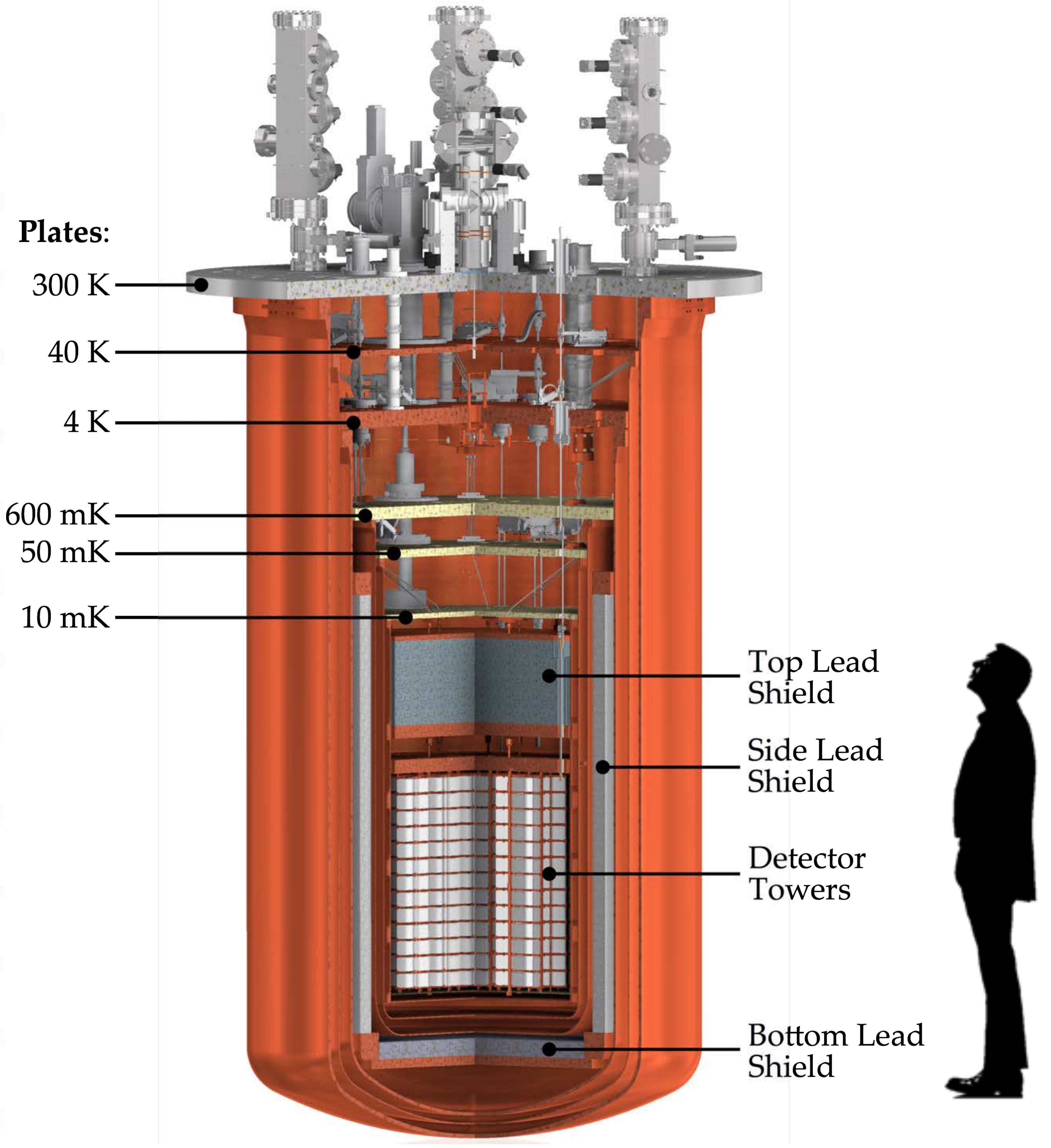


Detector Module



Tower

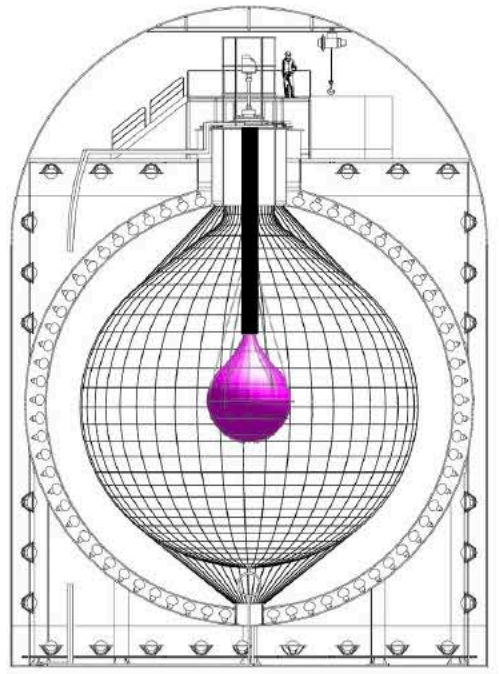




CUORE Detector

KamLAND-Zen

KamLAND-Zen 400

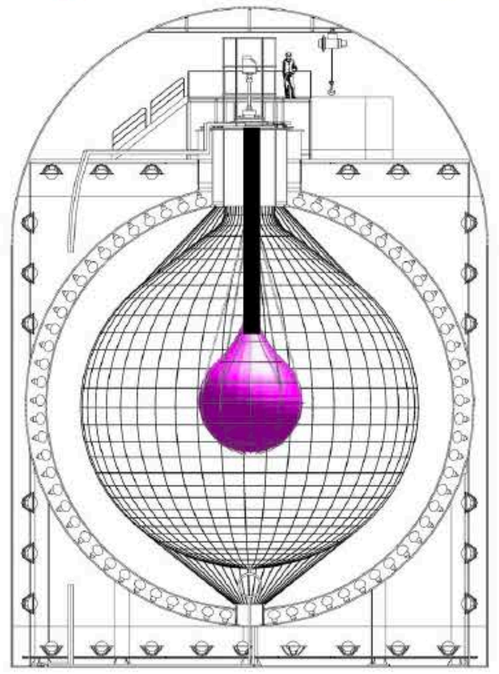


380kg deployed

$T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ yr

PRL117, 082503 (2016)

KamLAND-Zen 800



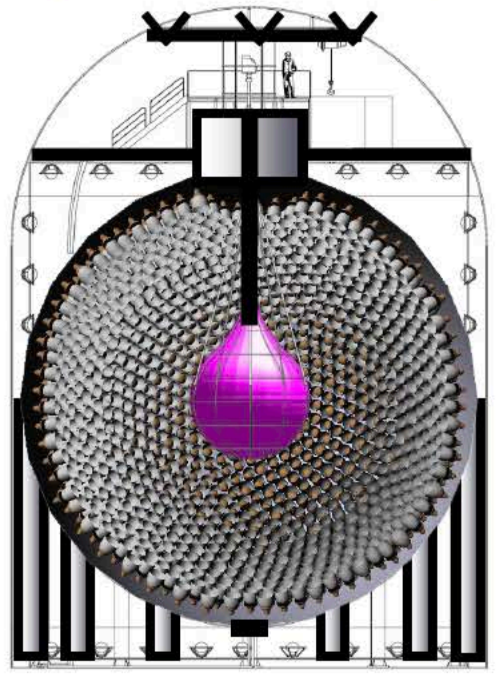
Now, 745kg deployed

$> 2.3 \times 10^{26}$ yr

PRL130, 051801 (2023)

Further improvements going on;
better neutron tagging
machine learning (ML) for long-lived tagging
ML for beta/gamma discrimination
muon-bundle tracking, and so on

KamLAND2-Zen



Mirror
HQE-PMT
new LS
full volume effective
w/ scintillation film

} x5 p.e.

1 ton planned (scalable)

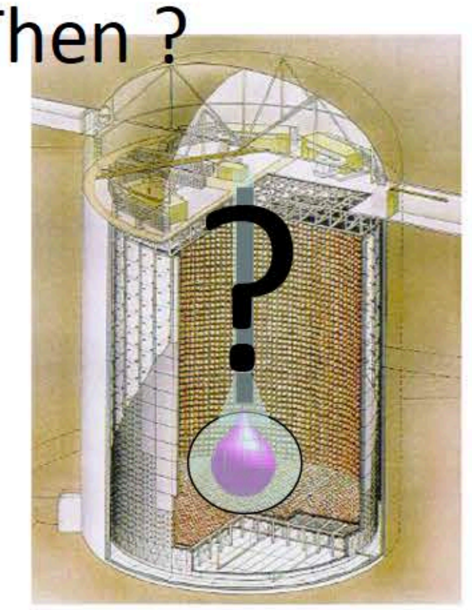
$> 2 \times 10^{27}$ yr (target sensitivity)

$< 12 \sim 53$ meV (corresponding mass limit)

3σ discovery potential is not studied, but ~1x10^{27} yr

Further technologies being developed
imaging sensor (1/10 reduction of long-lived BG)
high-p xenon deployment (2 times more xenon)

Then ?



It will not be a good choice for the single purpose, but this is multi-purpose detector.

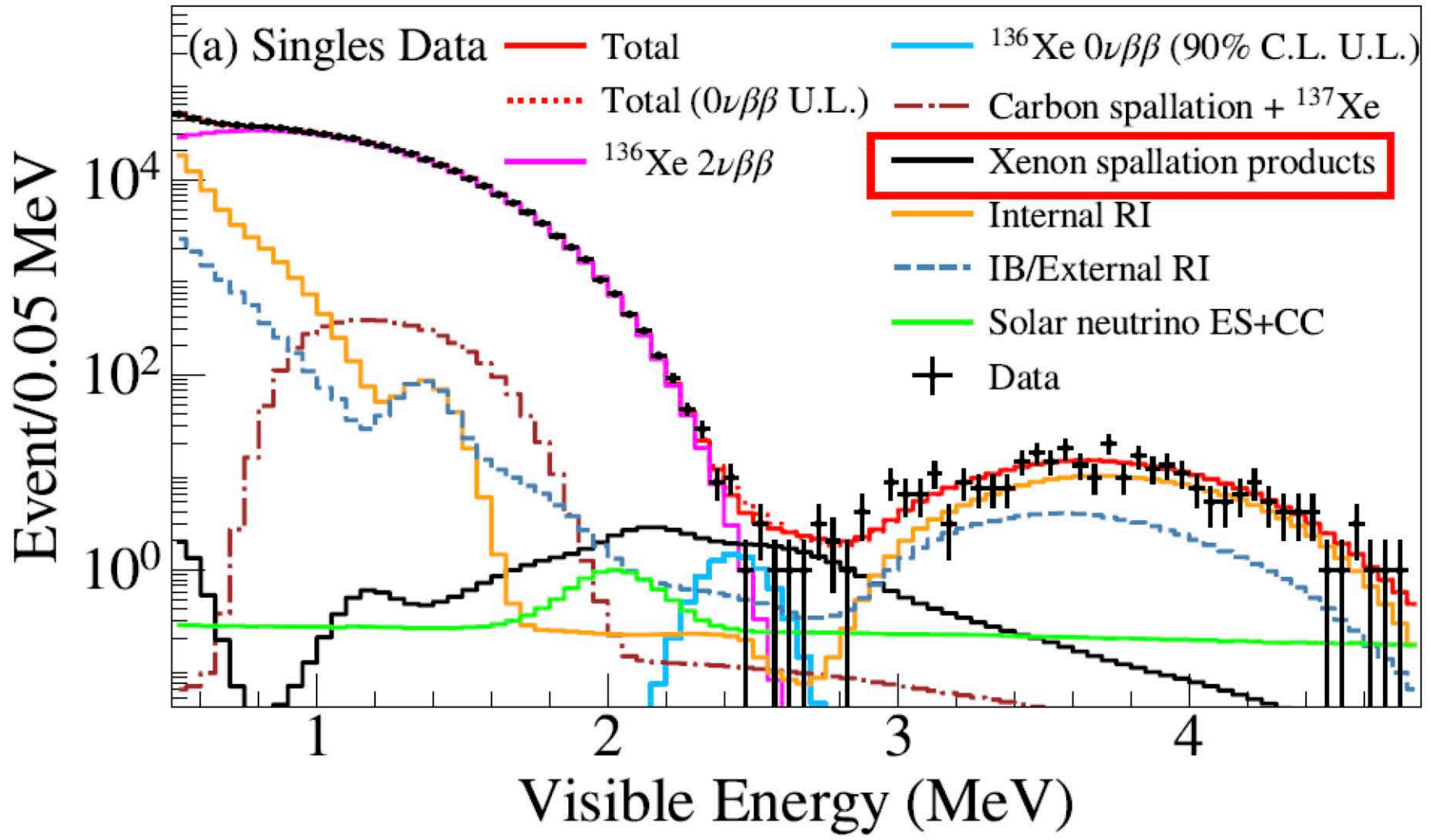
$> 2 \times 10^{28}$ yr
(guesstimated sensitivity)

w/ more than 20 ton xenon
imaging sensor
high-p xenon

For more xenon (possible source)
Extraction from nuclear spent fuel is considered.
More than 100 ton seems to be possible at 44% concentration of Xe-136 without centrifugal enrichment.

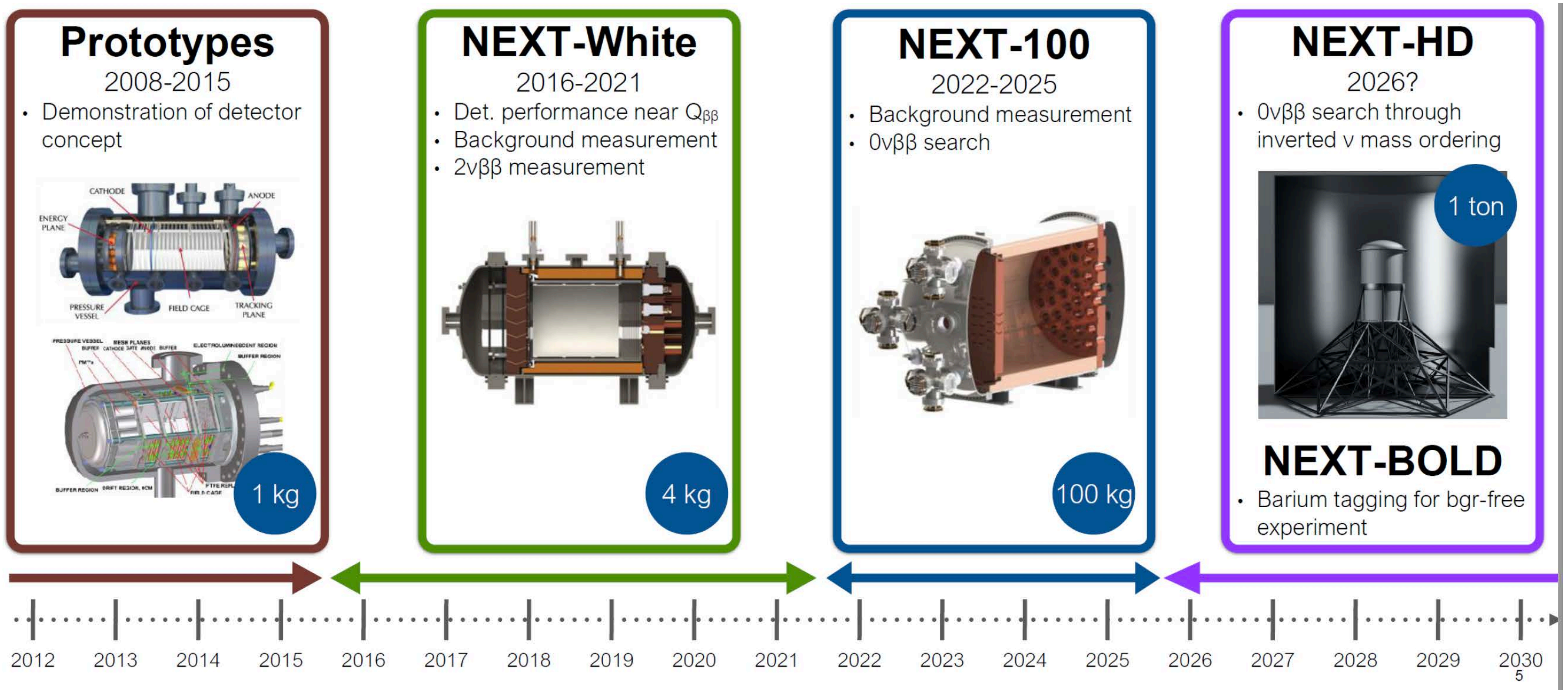
	36 months	atmospheric
$^{128}Xe/^{132}Xe$	$2.81 \cdot 10^{-3}$	$7.13 \cdot 10^{-2}$
$^{129}Xe/^{132}Xe$	$4.7 \cdot 10^{-6}$	0.9832
$^{130}Xe/^{132}Xe$	$3.32 \cdot 10^{-4}$	0.1518
$^{131}Xe/^{132}Xe$	0.3756	0.7876
$^{134}Xe/^{132}Xe$	1.3433	0.3883
$^{136}Xe/^{132}Xe$	2.1176 44%	0.3298 8.9%

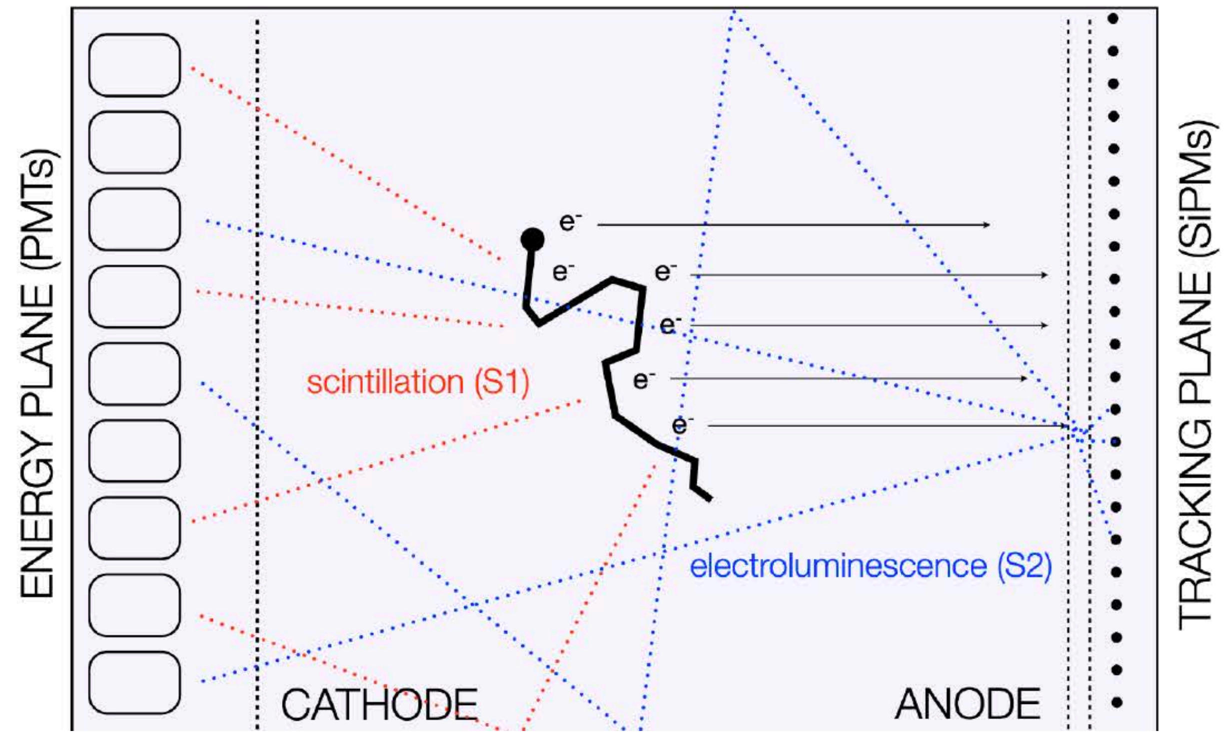
Results from Kam-Zen 800 (arXiv 2203.02139) March 2022



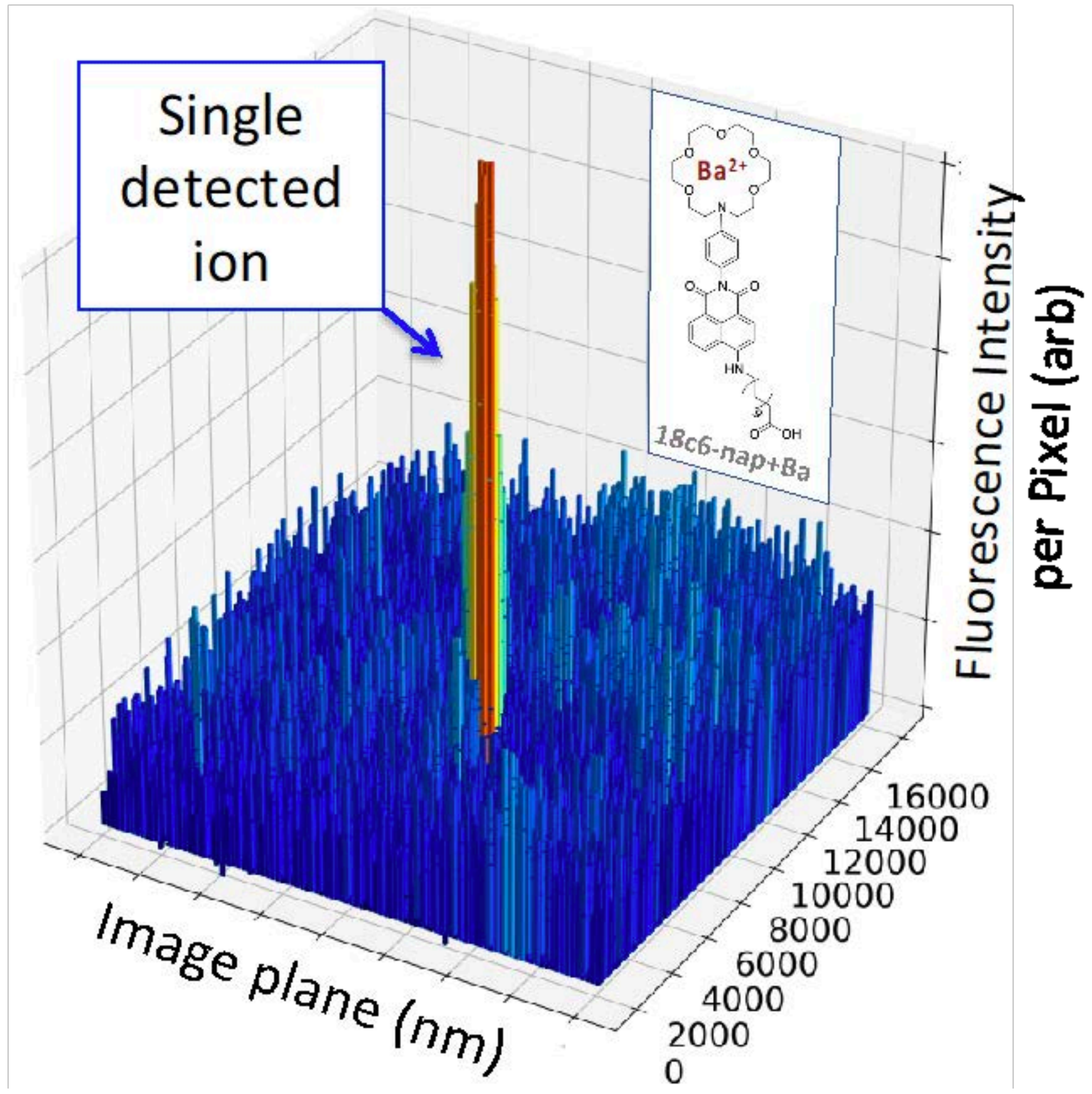
$T^{1/2} > 2.3 \times 10^{26}$ yr (Combined Kam-Zen 400 and 800)
$\langle M_{\beta\beta} \rangle$ is < 36 – 156 meV

NEXT





- **NEXT uses enriched ^{136}Xe gas at high pressure and provides tracks of individual electrons.**
- **There is also a program of extracting Ba^{+} through fluorescence in organic molecules aiming at NEXT-BOLD.**

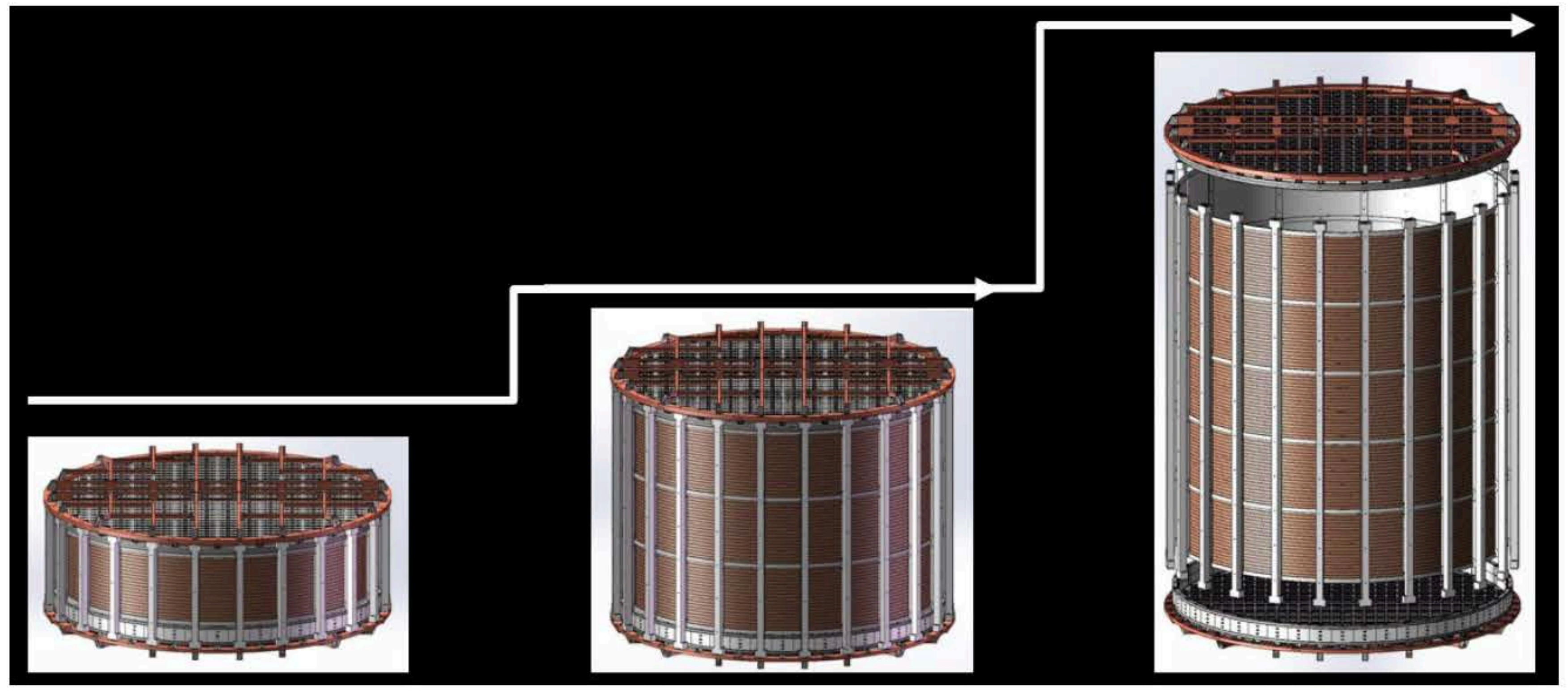


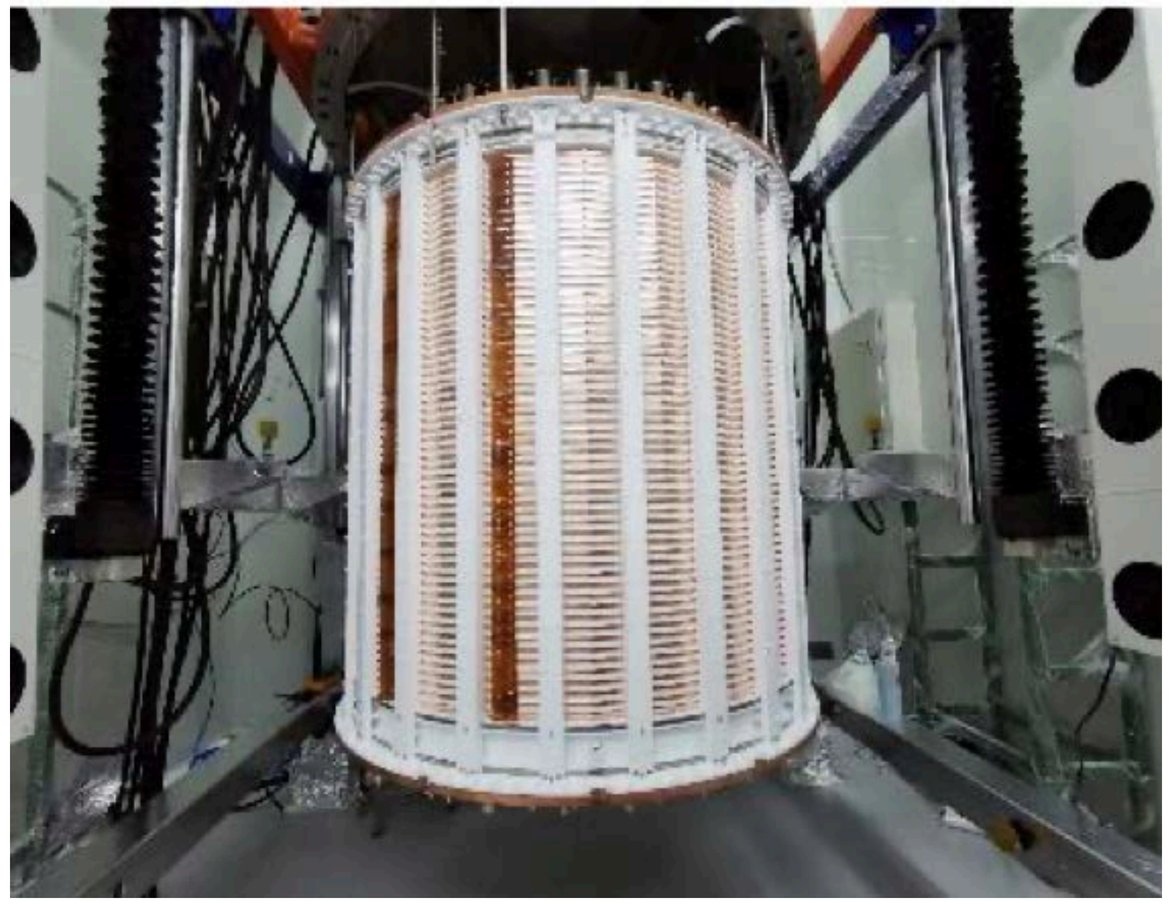
NEXT aims to capture and image Ba2+ions produced in double beta decay of 136Xe.

PandaX - xT

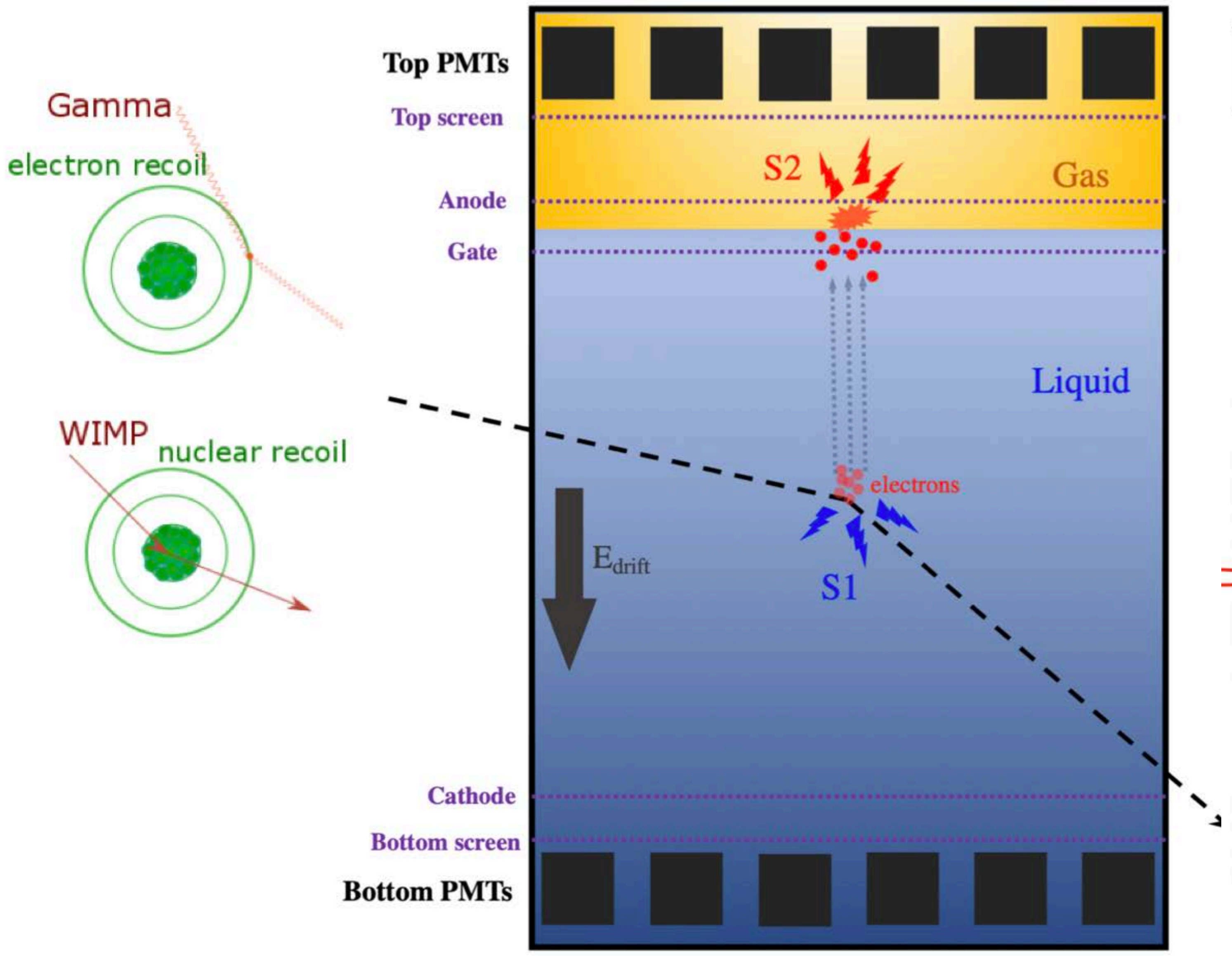
Now operating PandaX-4T (natural xenon)

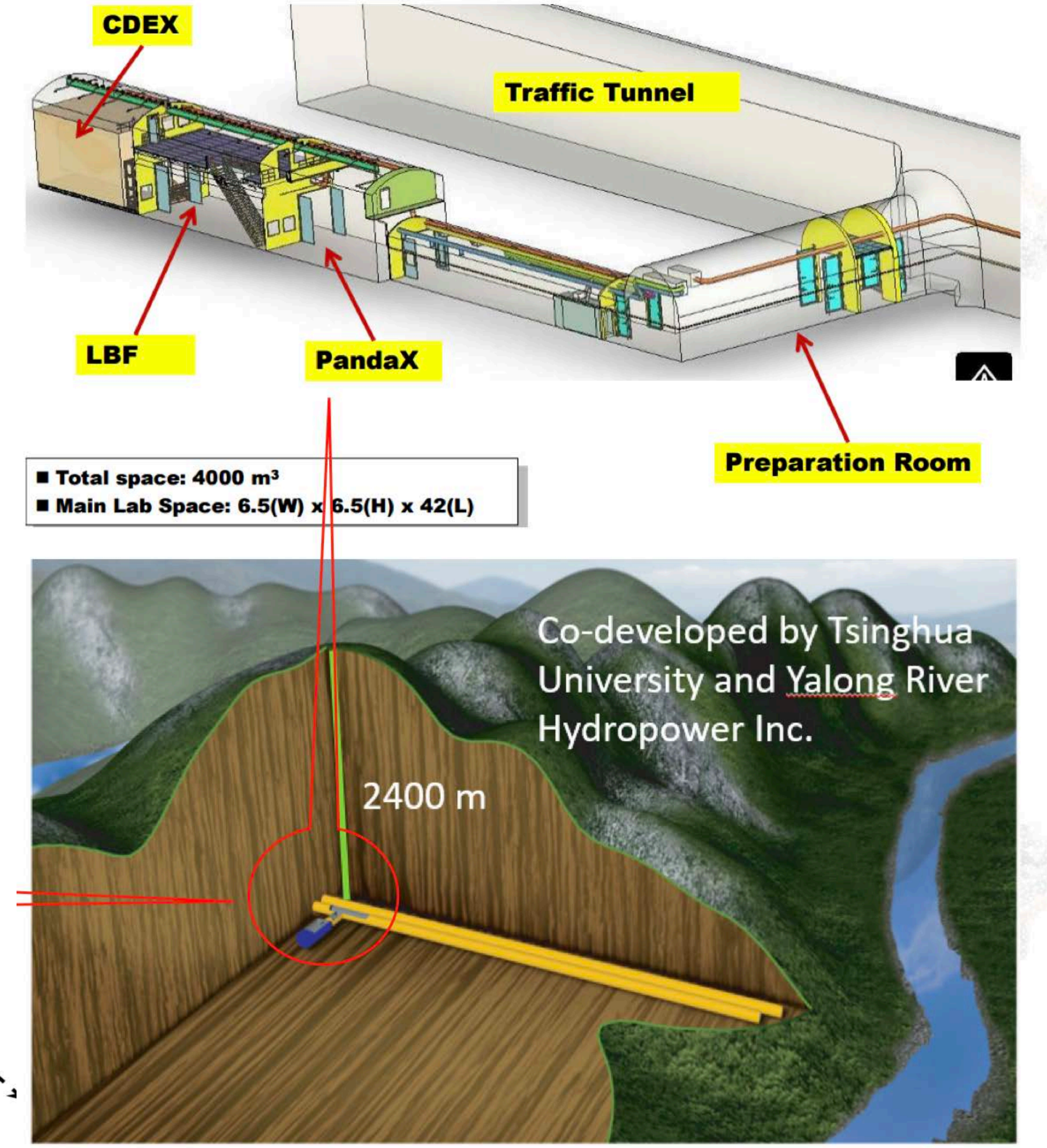
Step-wise upgrade in the same experimental hall based on possessed xenon towards 43-ton (active), 47-ton (total) natural xenon



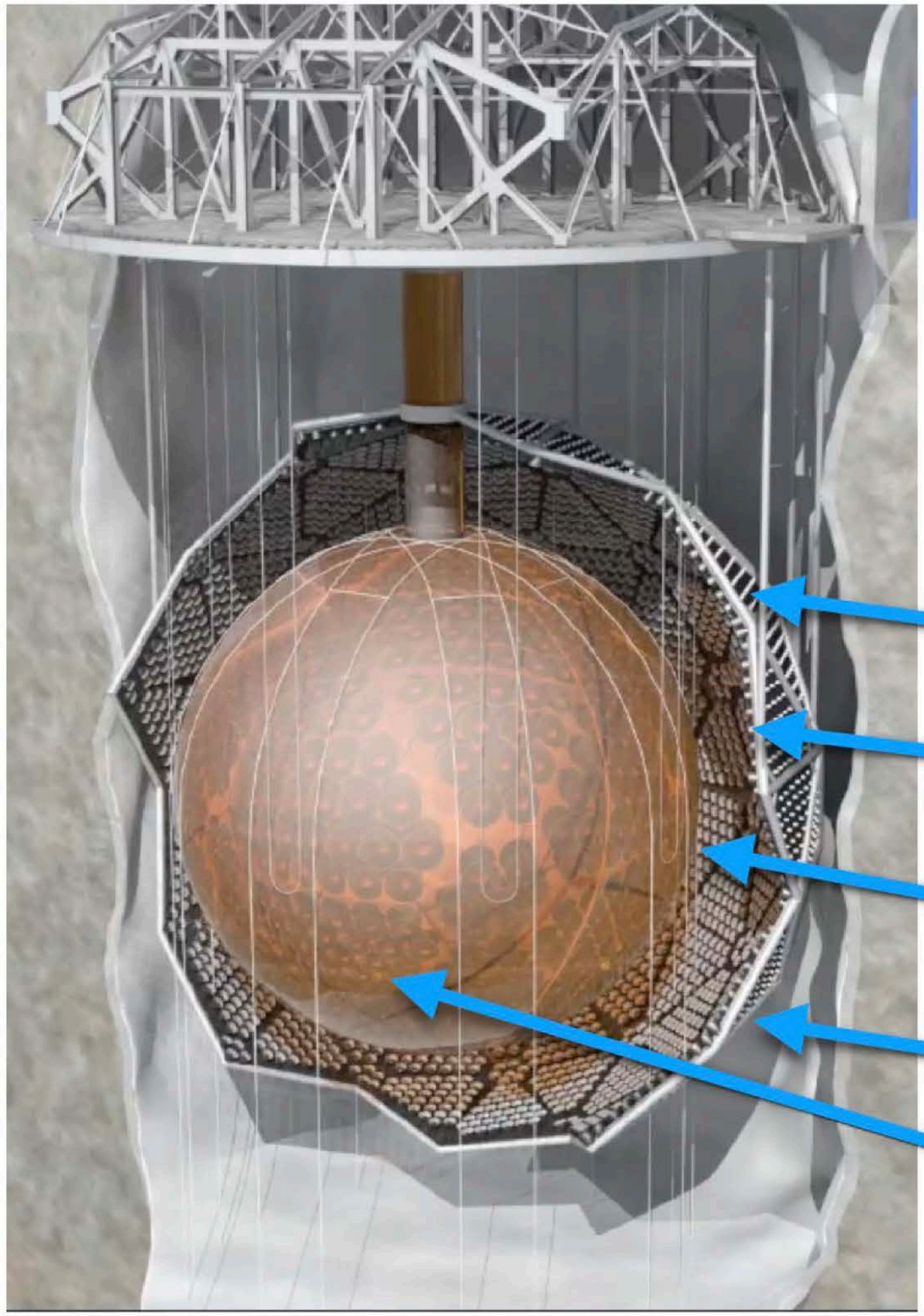


Dual Phase Xenon TPC





SNO+



- **2km** underground in **SNOLAB**, Canada
- Infrastructure repurposed from **SNO**:
  - New calibration systems
  - Upgraded DAQ and electronics
  - New hold-down ropes
  - Scintillator Plant + Tellurium synthesis and purification

~9300 PMTs

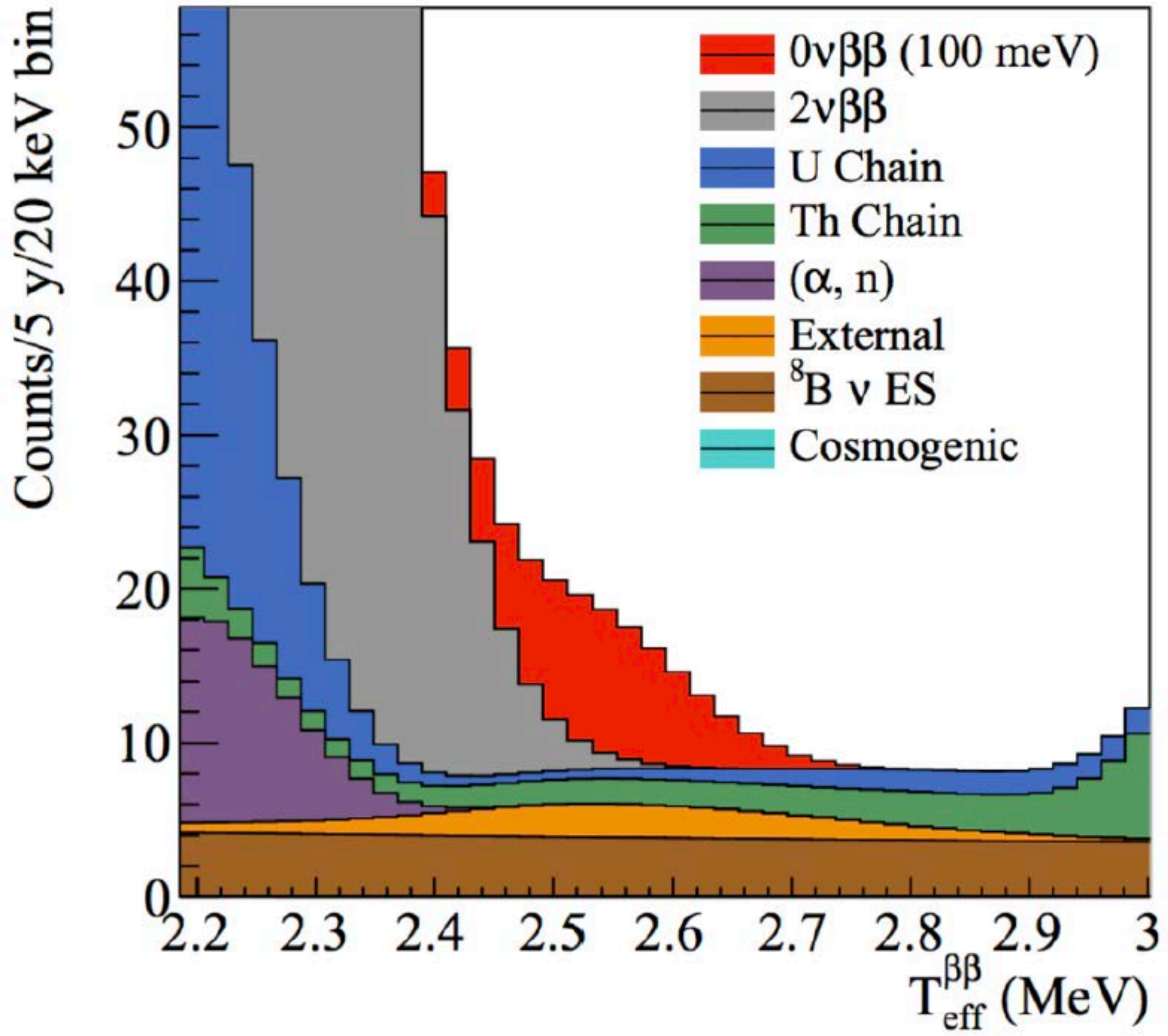
18m diameter PMT Support Structure

12m diameter Acrylic Vessel

7kt ultra pure water shielding

780t Liquid Scintillator to be loaded with 0.5% ^{130}Te initially

Increase to 3% planned for future



SNO+
5 years at 0.5% Te Loading:
1300 kg ^{130}Te

$m_{\beta\beta}$ < 30-130 meV (99.7% CL)

Presently running with liquid scintillator for other physics and evaluating backgrounds. Te projected for early 2025.

THEIA - Hybrid Neutrino Detection

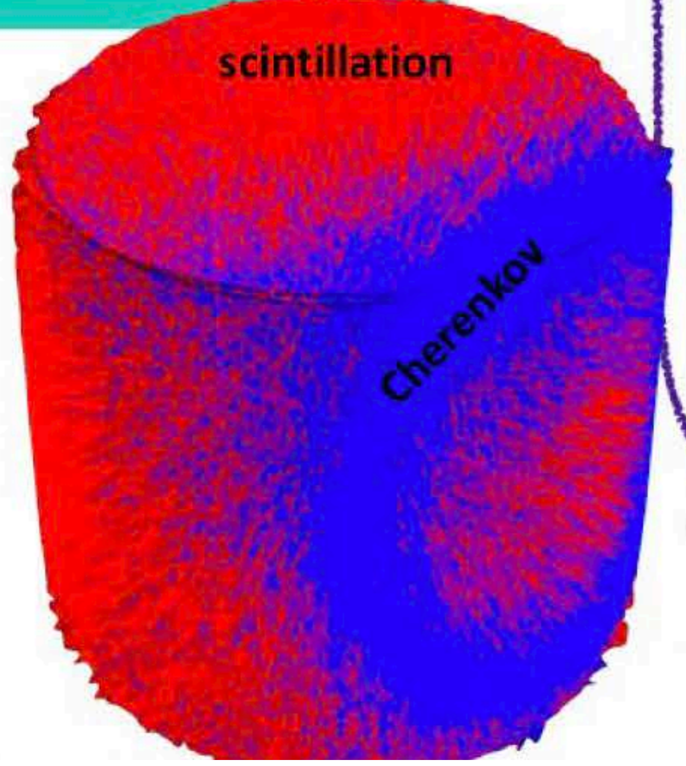
Combine Cherenkov + scintillation in a single, large detector

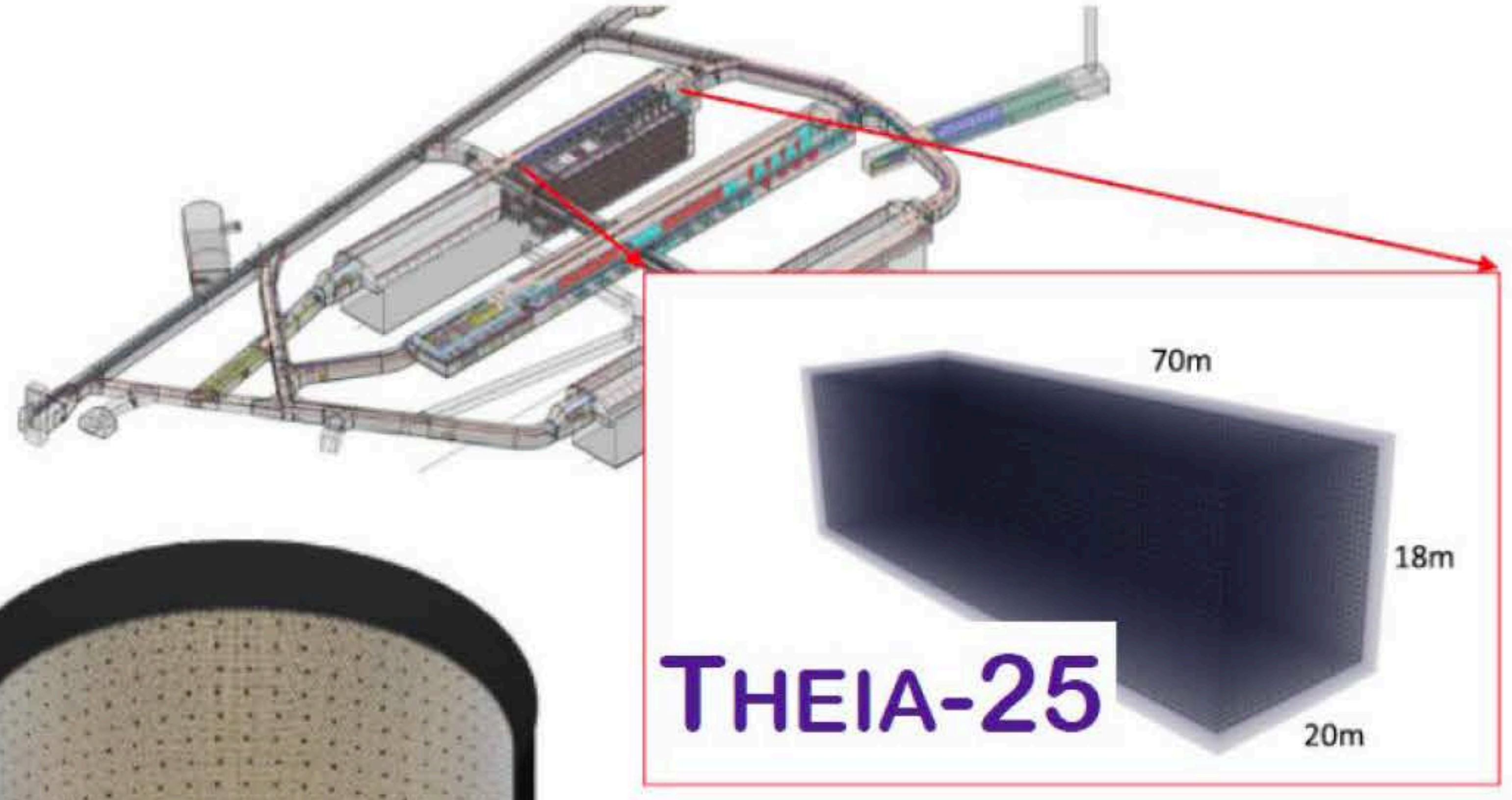
Directional information from Cherenkov topology + excellent resolution from high-yield scintillation

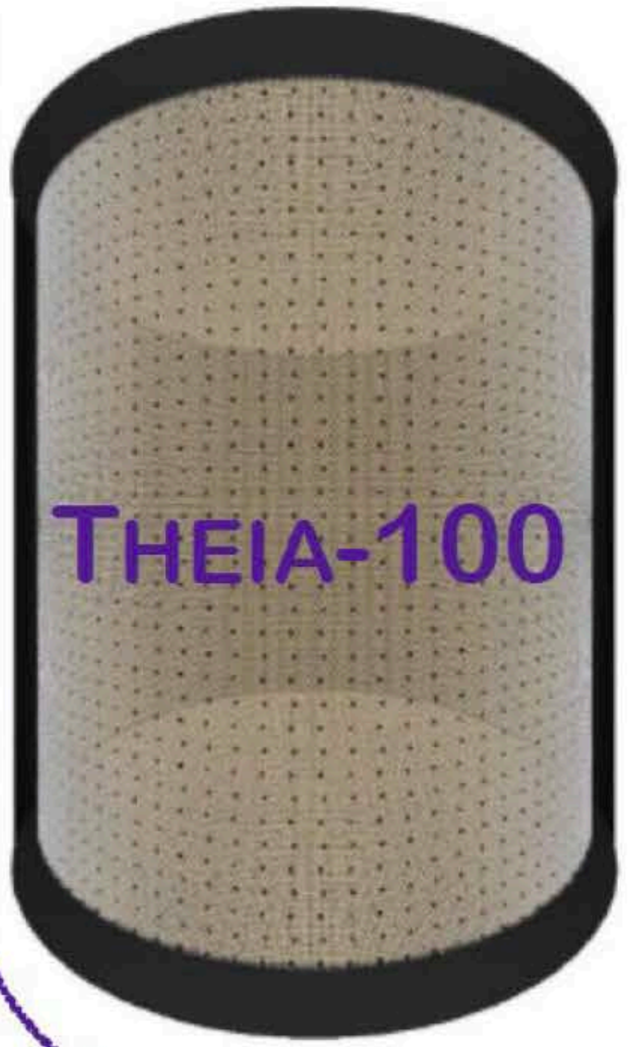
Can interrogate a uniquely broad program of physics, from sub-MeV to multi-GeV

Cutting-edge developments in target material and photon detection

Novel (Wb)LS
Fast photon detectors
LAPPDs
Spectral sorting



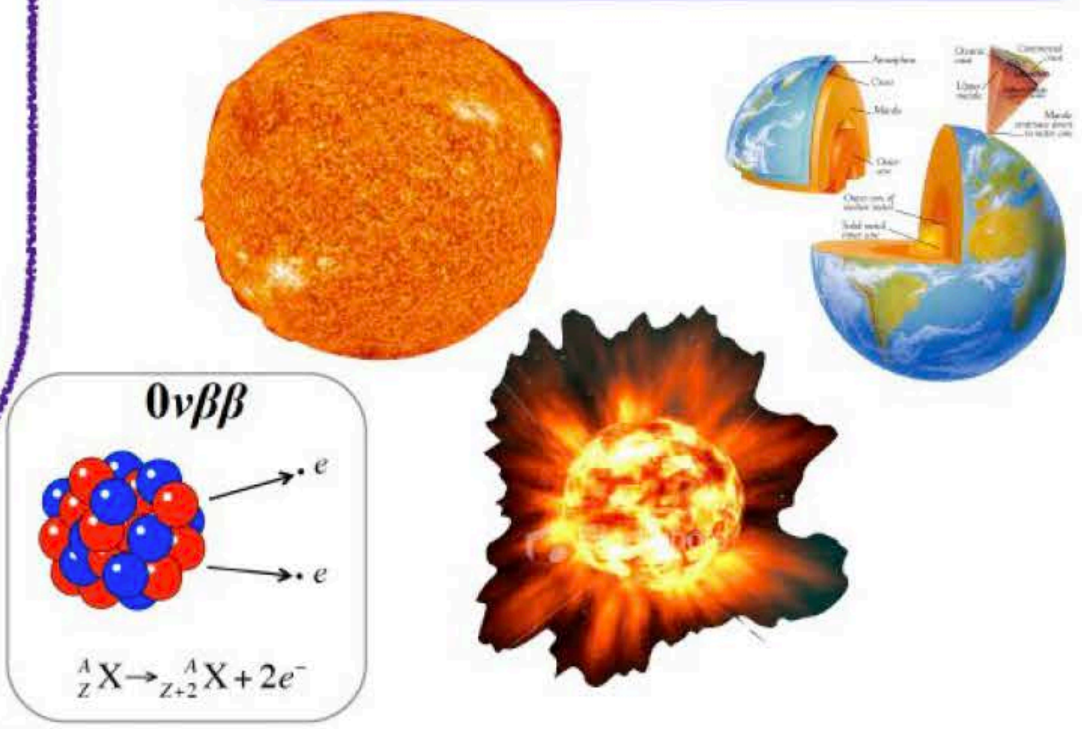




Large, multipurpose detector
- Baseline: 25ktonne (17kt FV)
- Ideal: 100 ktonne (70kt FV)

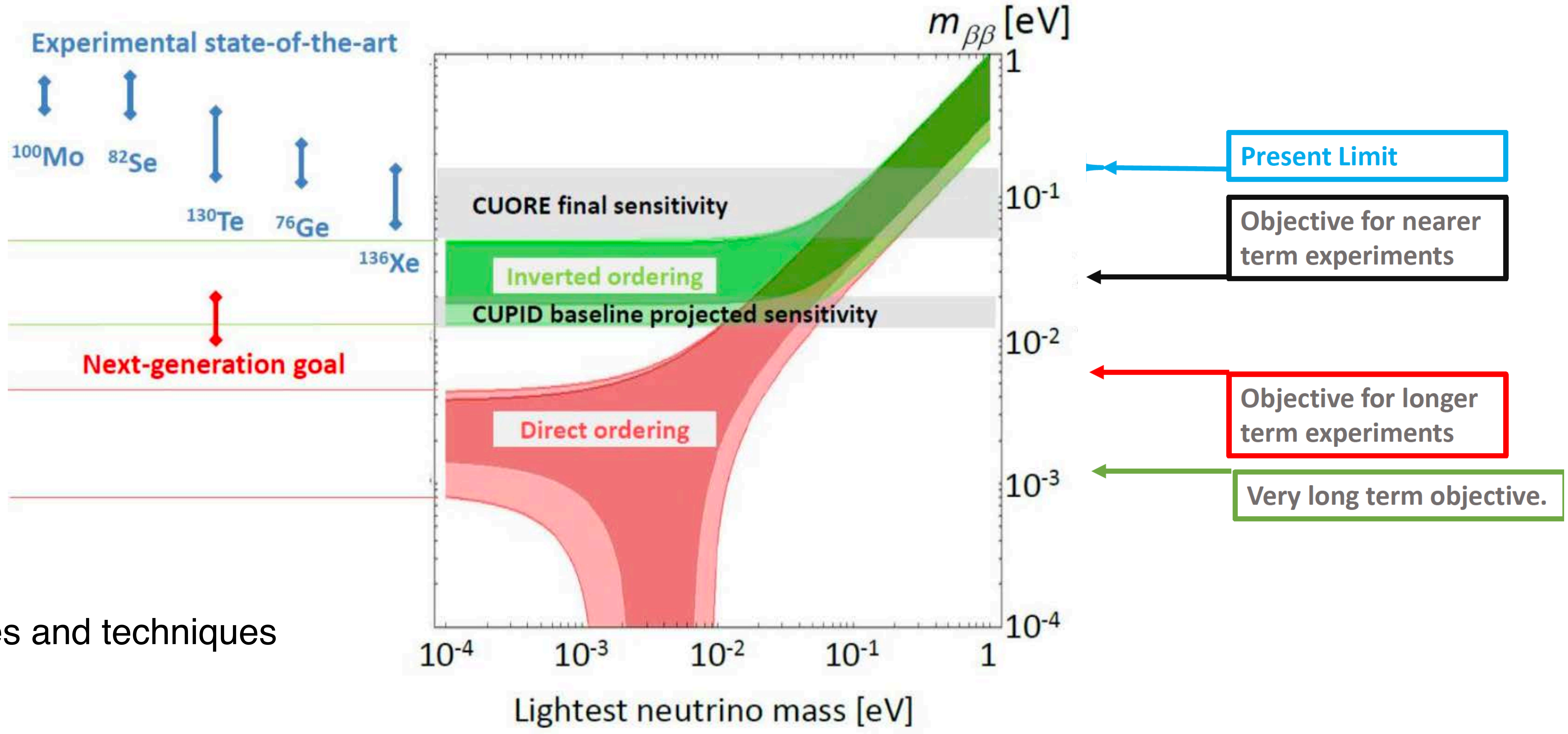
Broad physics program: Fundamental nature of matter *and* multi-messenger astrophysics

0νββ, CPV, solar, supernova, geo, nucleon decay



THEIA: An advanced optical neutrino detector
Eur. Phys. J. C 80, 416 (2020)

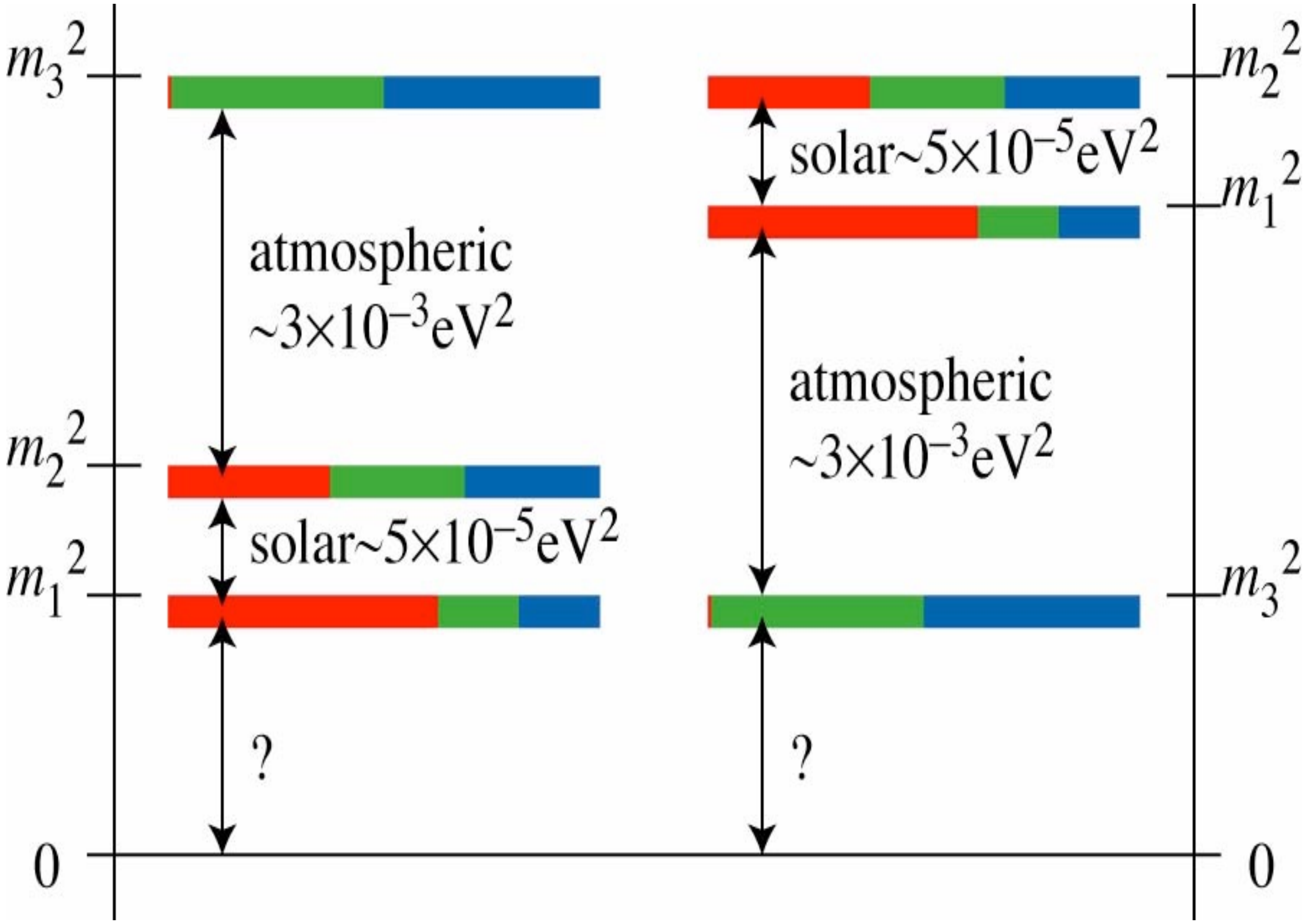
Sensitivity of Future 0νββ Searches



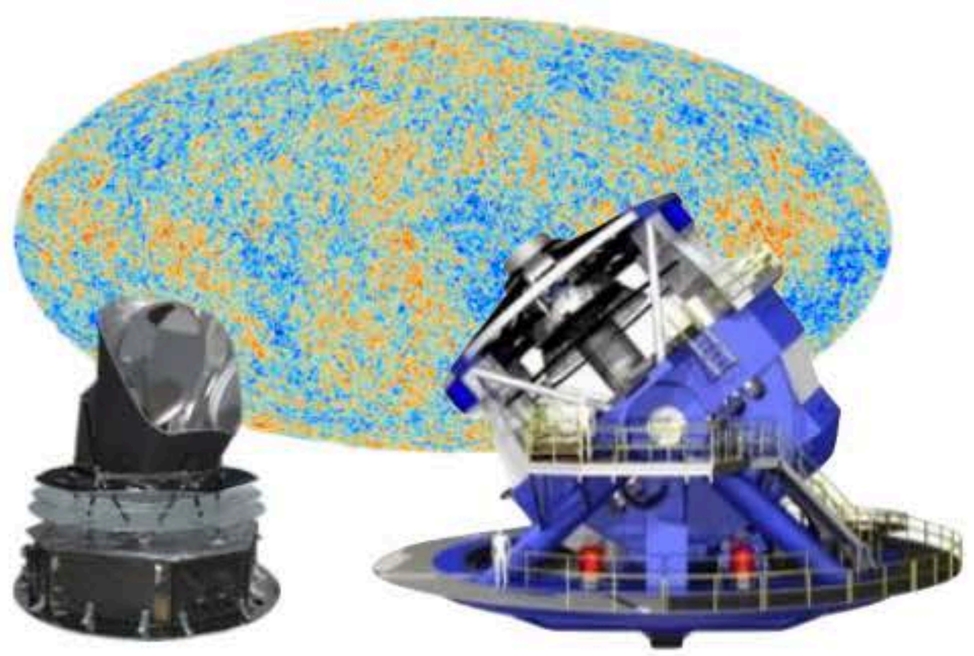
variety of isotopes and techniques important

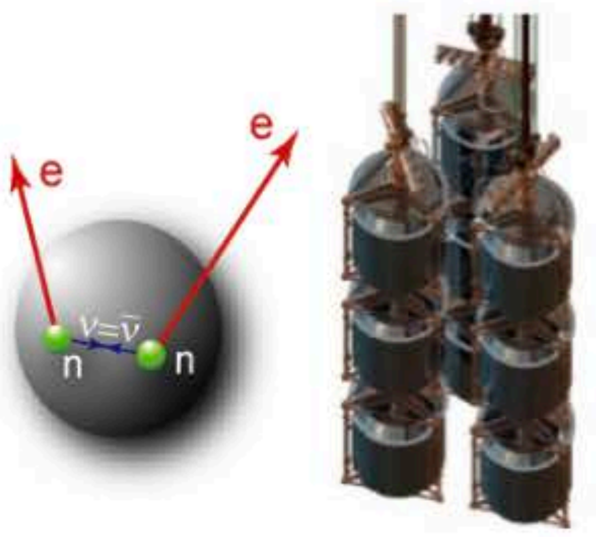
Designing for discovery experiments
A discovery in the next 10-15 years possible

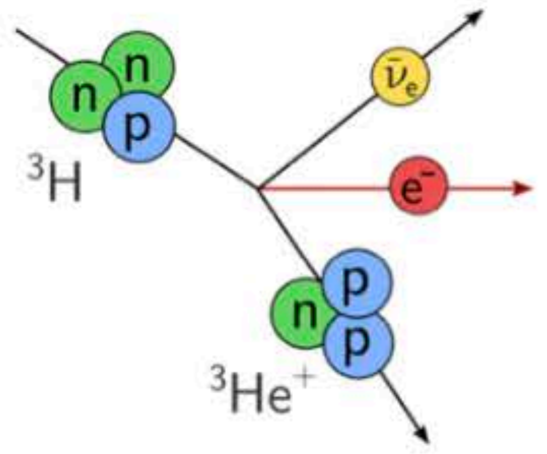
What is the mass scale?

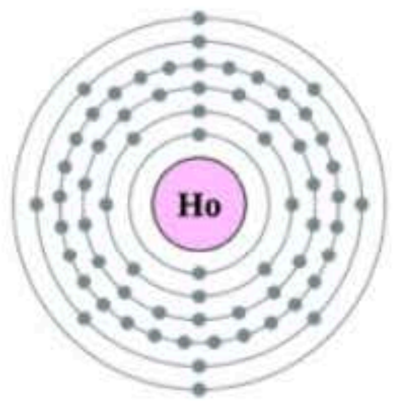


Paths to the Neutrino Mass Scale





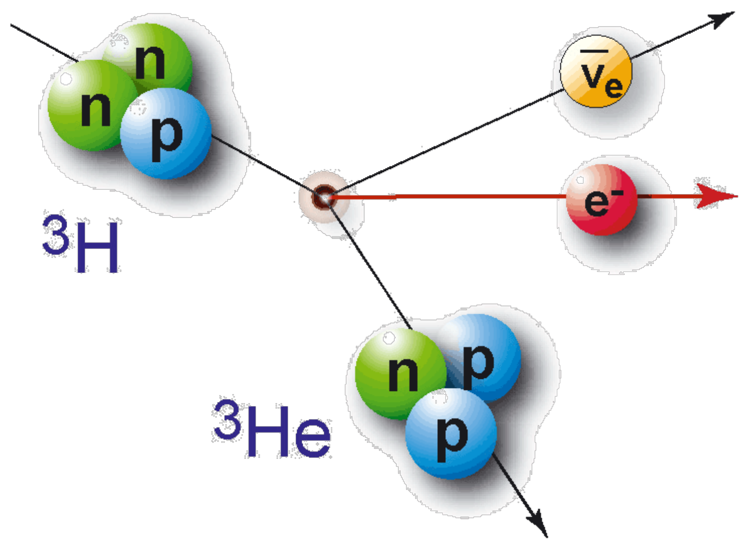


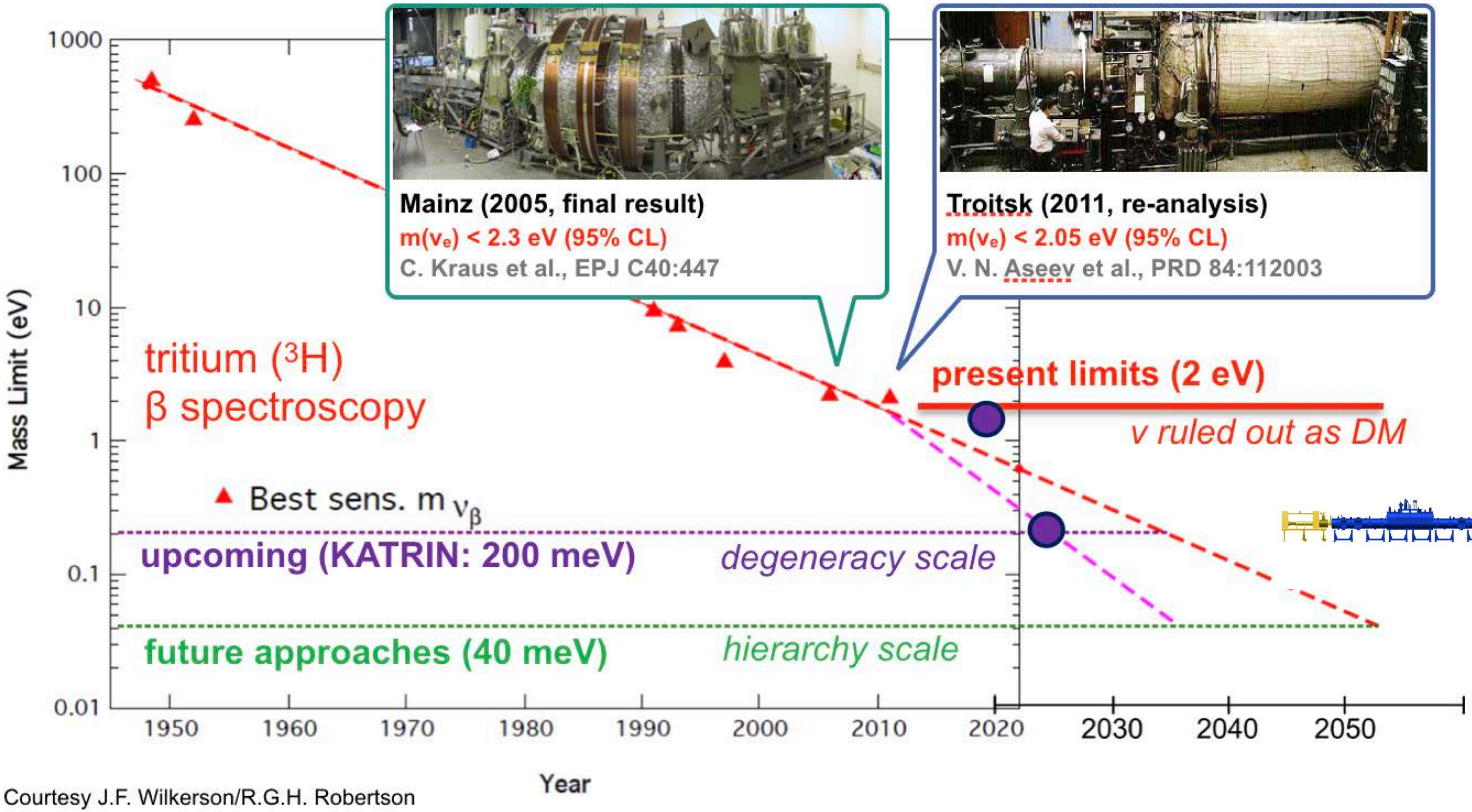


	Cosmology	Search for 0νββ	β-decay & electron capture
Observable	$M_\nu = \sum_i m_i$	$m_{\beta\beta}^2 = \left\| \sum_i U_{ei}^2 m_i \right\|^2$	$m_\beta^2 = \sum_i \|U_{ei}\|^2 m_i^2$
Present upper limit	~0.1 – 0.6 eV	~0.1 – 0.4 eV	~~2 eV~~ **0.8 eV**
Potential: near-term (long-term)	60 meV (15 meV)	50 – 200 meV (20 – 40 meV)	200 meV (40 – 100 meV)
Model dependence	Multi-parameter cosmological model	- Majorana nature of ν, lepton number violation - BSM contributions other than m(ν)? - Nuclear matrix elements	**Direct,** only kinematics; no cancellations in incoherent sum

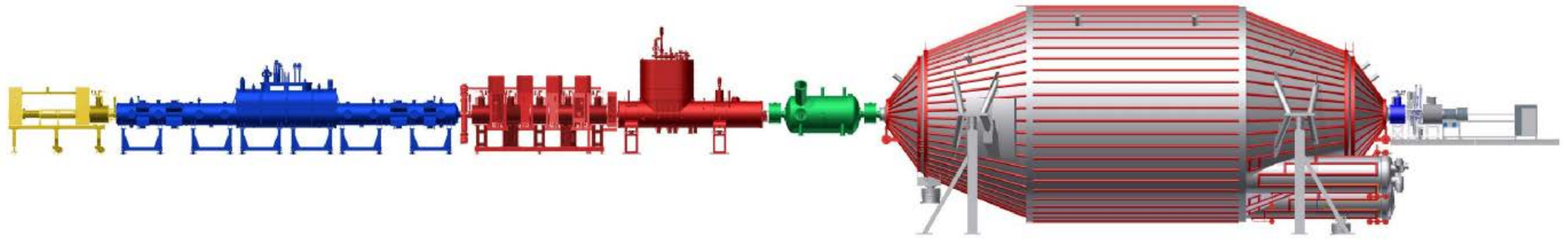
K. Valerius

Direct Neutrino Mass Searches



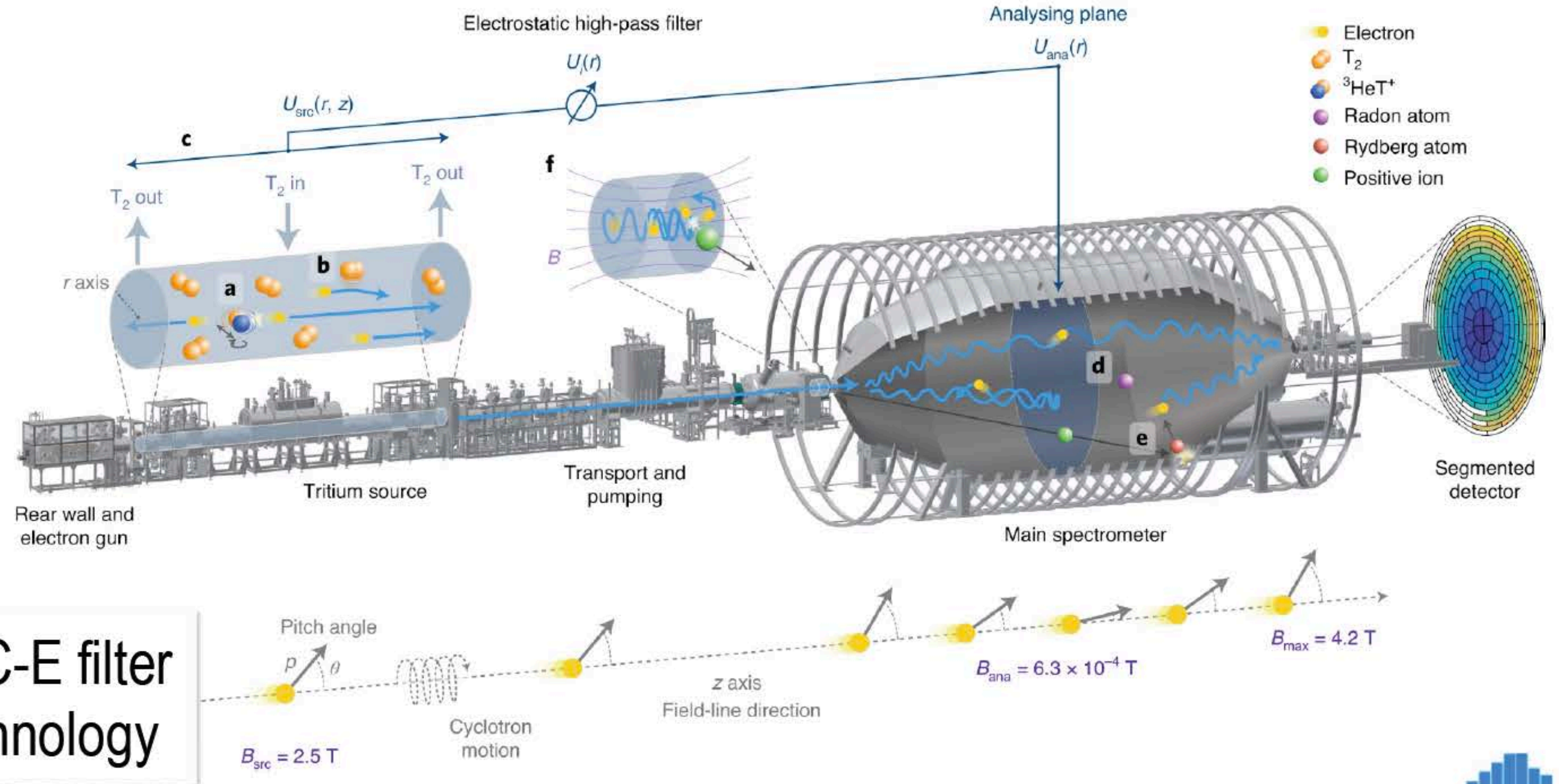


Courtesy J.F. Wilkerson/R.G.H. Robertson

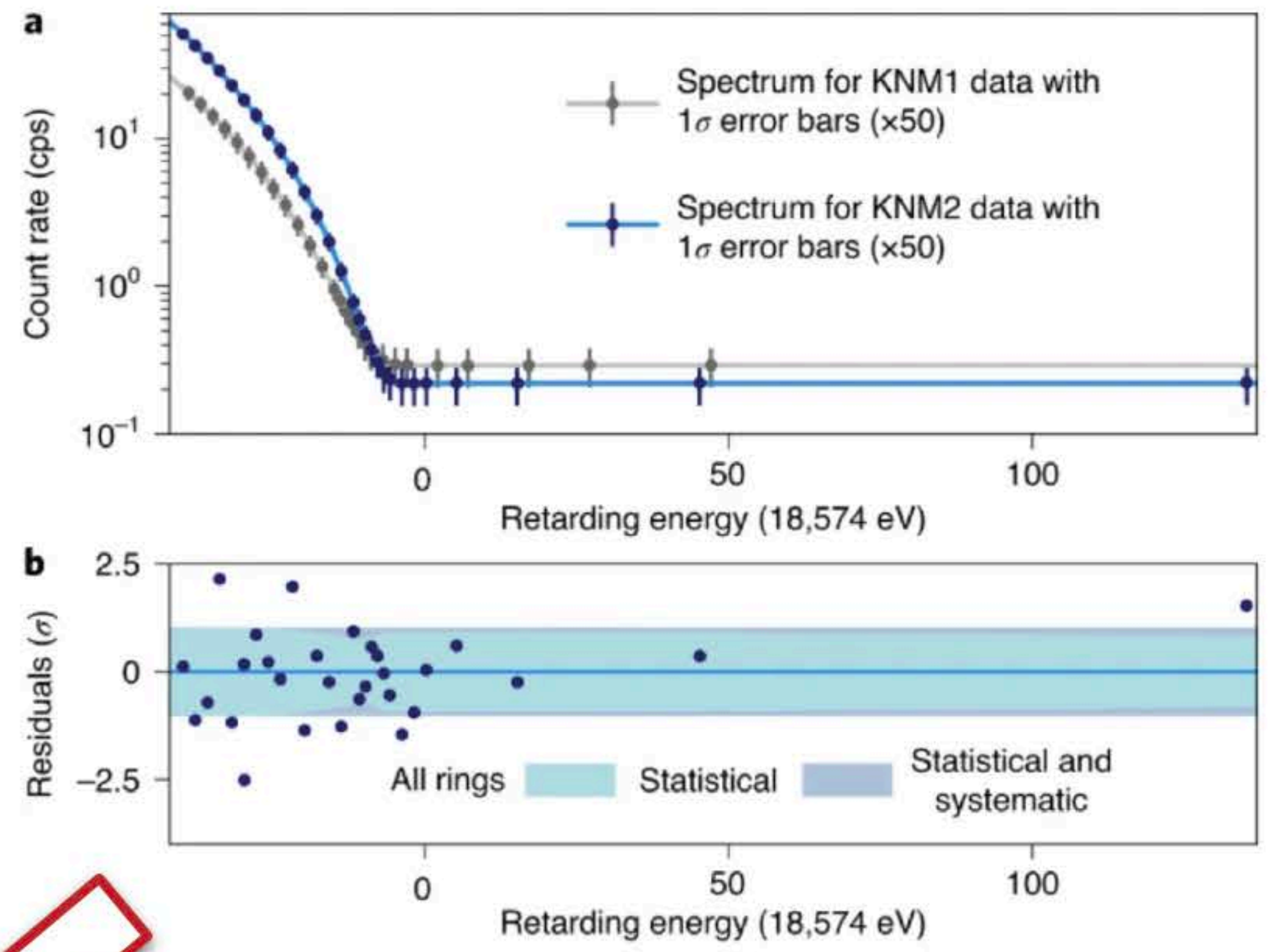


Tritium experiments define the mass limit

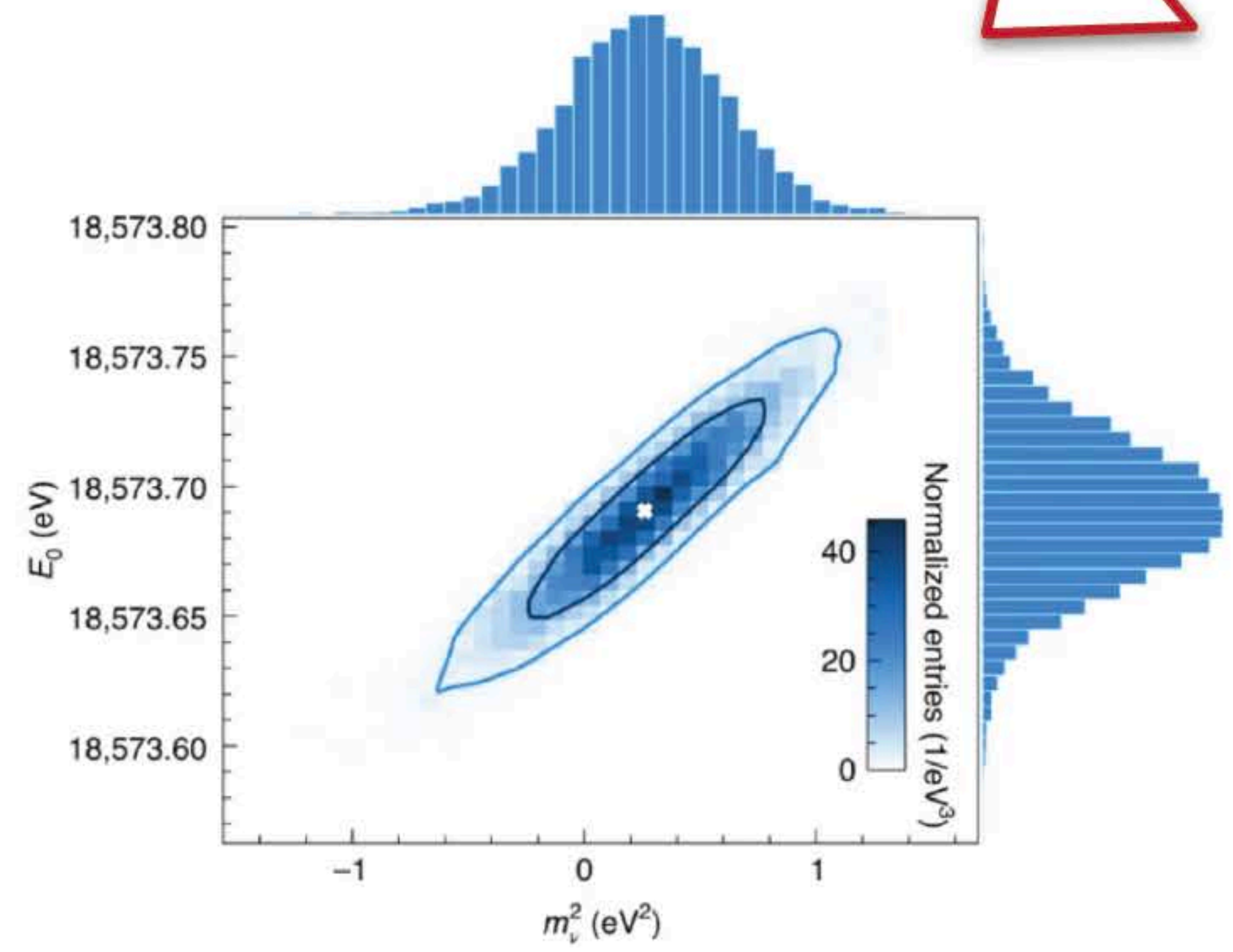
KATRIN



MAC-E filter technology



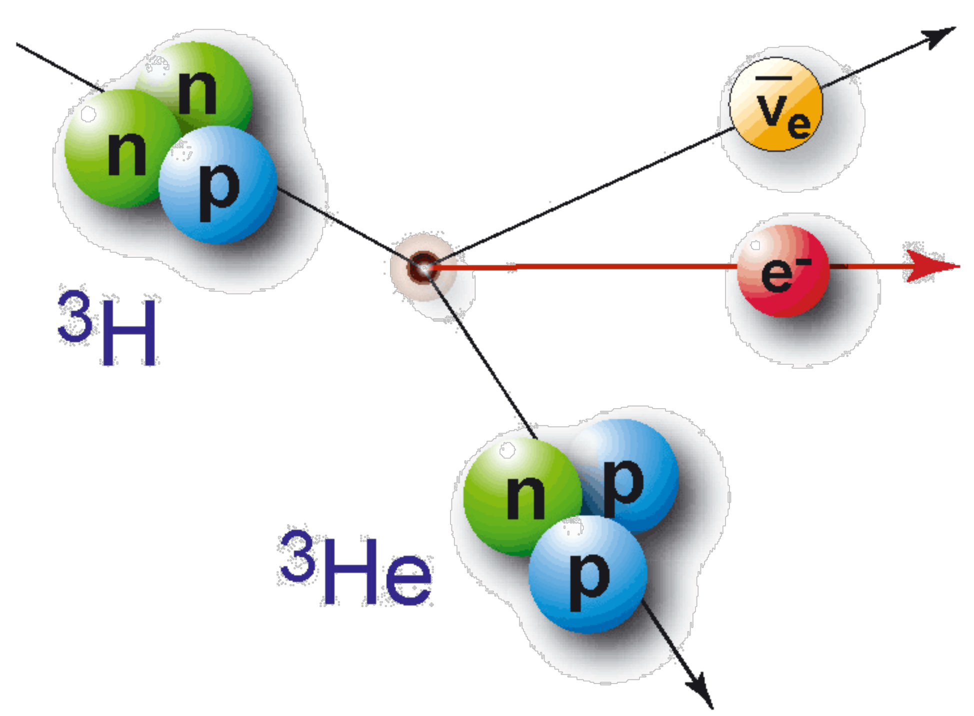
- Source decay rate > 10^{11} Bq
- Tritium suppression > 10^{12}
- MAC-E filter width: 0.93 eV @ 18.6 keV
- Main spectrometer at < 10^{-10} mbar
- Exquisite MC model of experiment

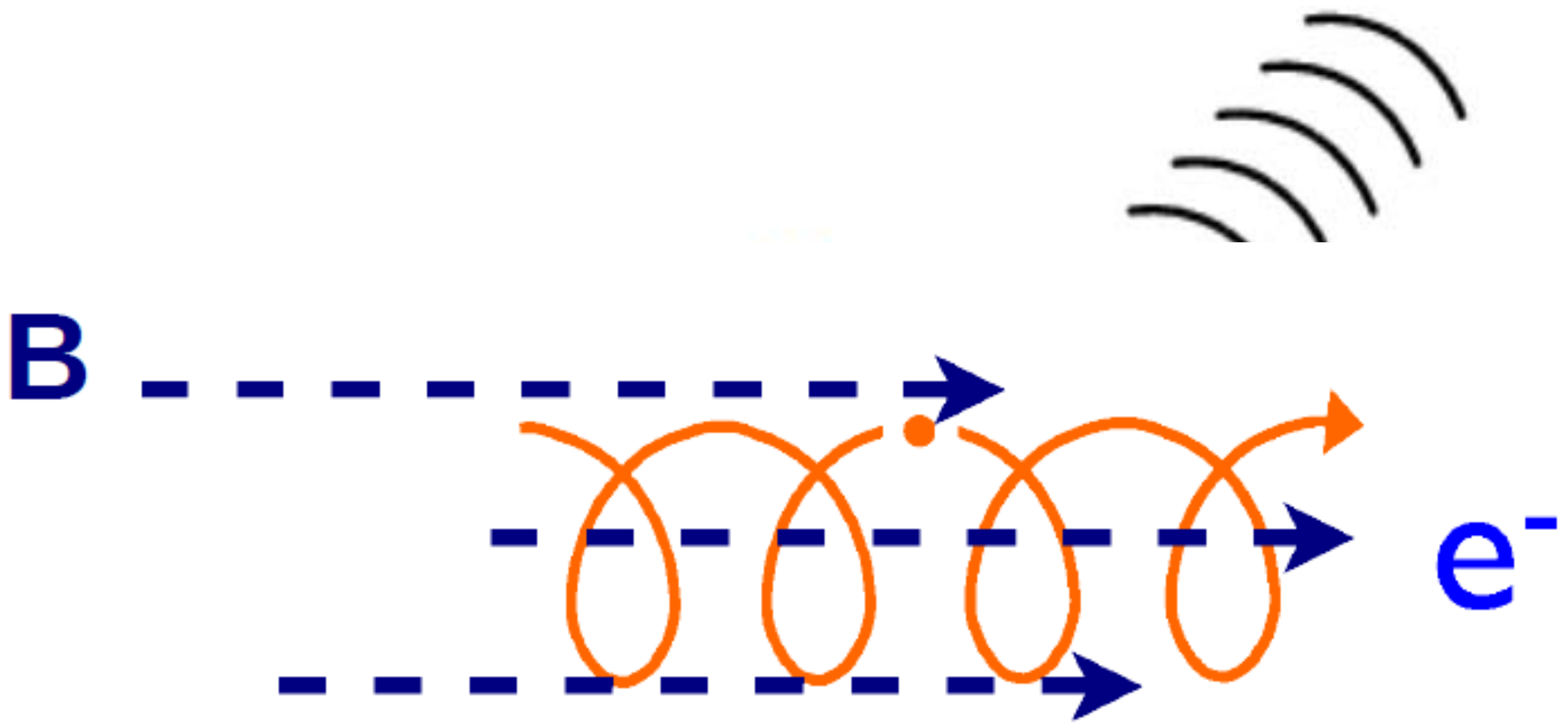


Best upper limit on neutrino mass
$m_\nu < 0.8\,\mathrm{eV/c^2}$ at 90 % CL

Anticipated sensitivity:
$m_\nu < 0.2\,\mathrm{eV/c^2}$ at 90 % CL

Project 8 - A New Approach to Measuring Neutrino Mass



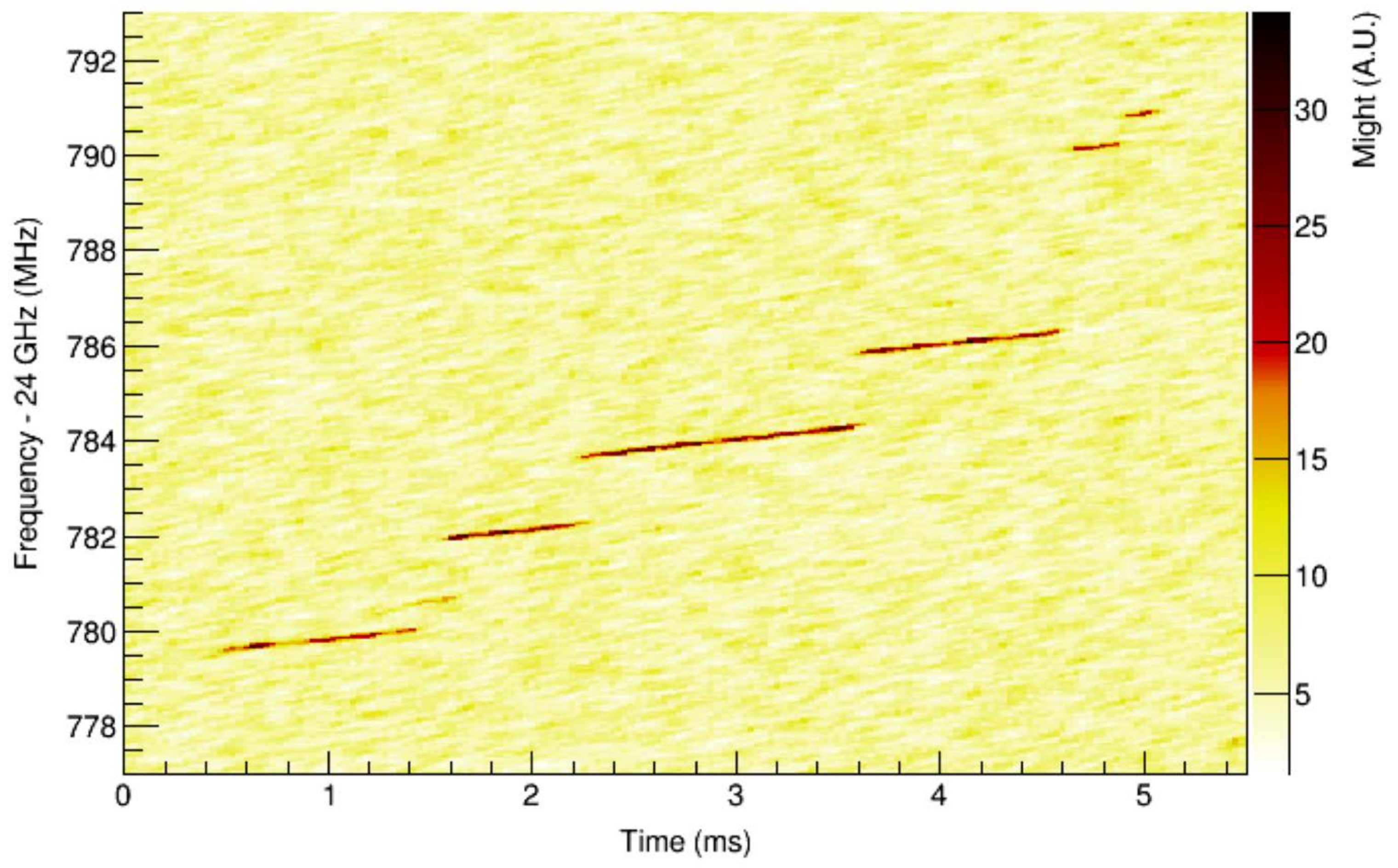


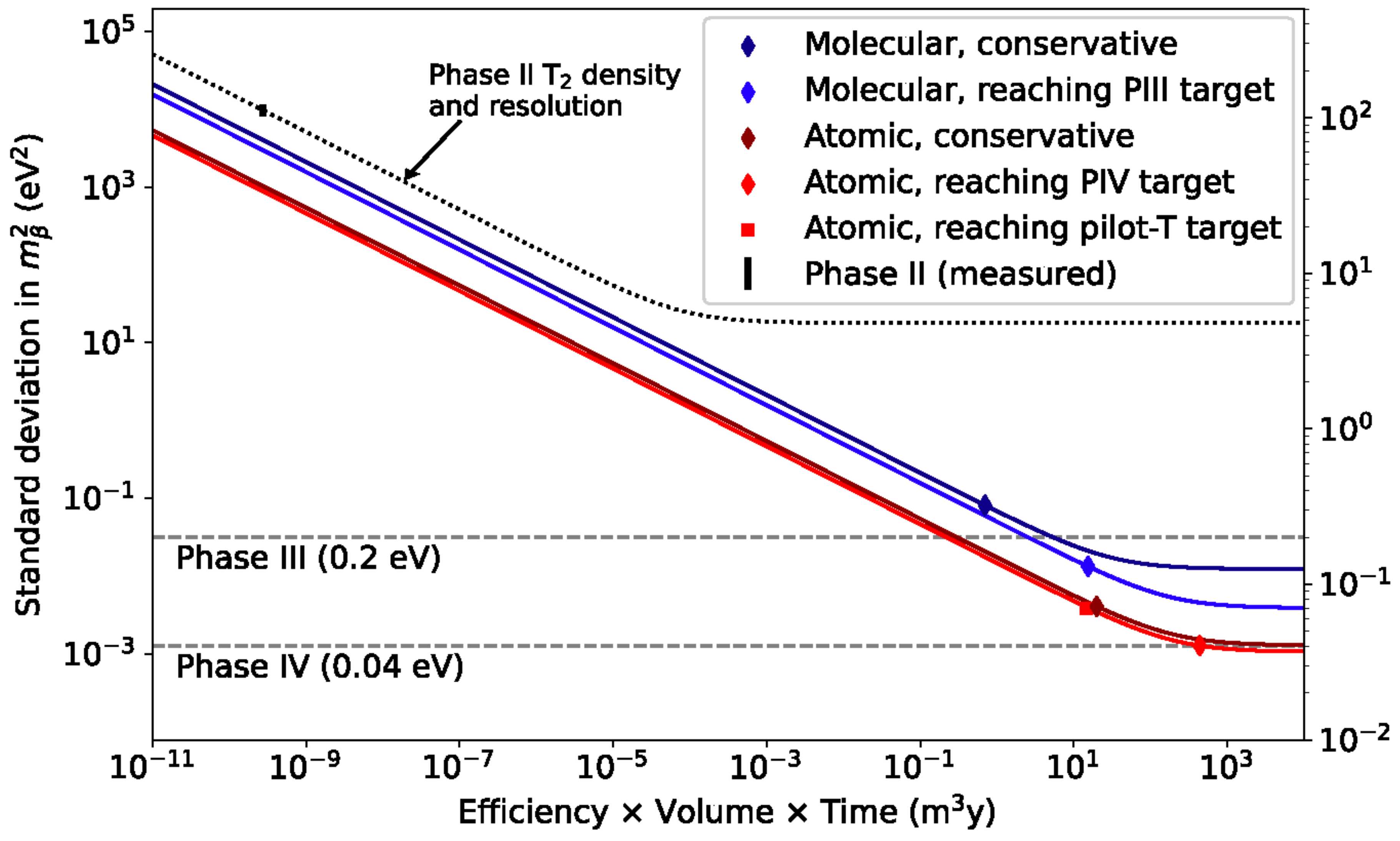
Cyclotron Radiation Emission Spectroscopy (CRES)

In uniform magnetic field, a charged particle will have a helical trajectory

Accelerating electron will radiate EM waves at frequency:

$$f_{Cyc} = \frac{1}{2\pi}\frac{qB}{m\gamma} = \frac{1}{2\pi}\frac{qB}{m_e + E_e}$$



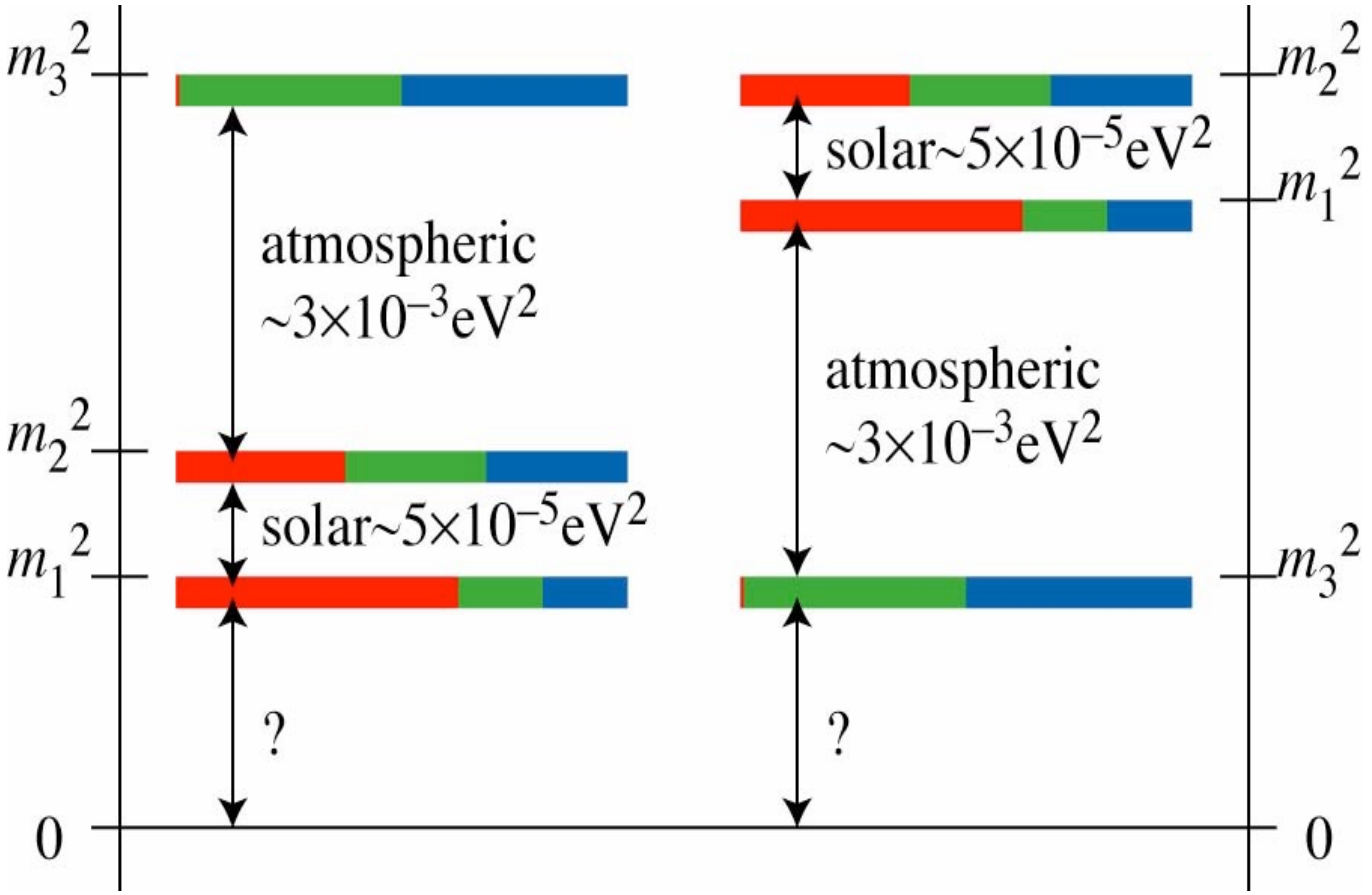


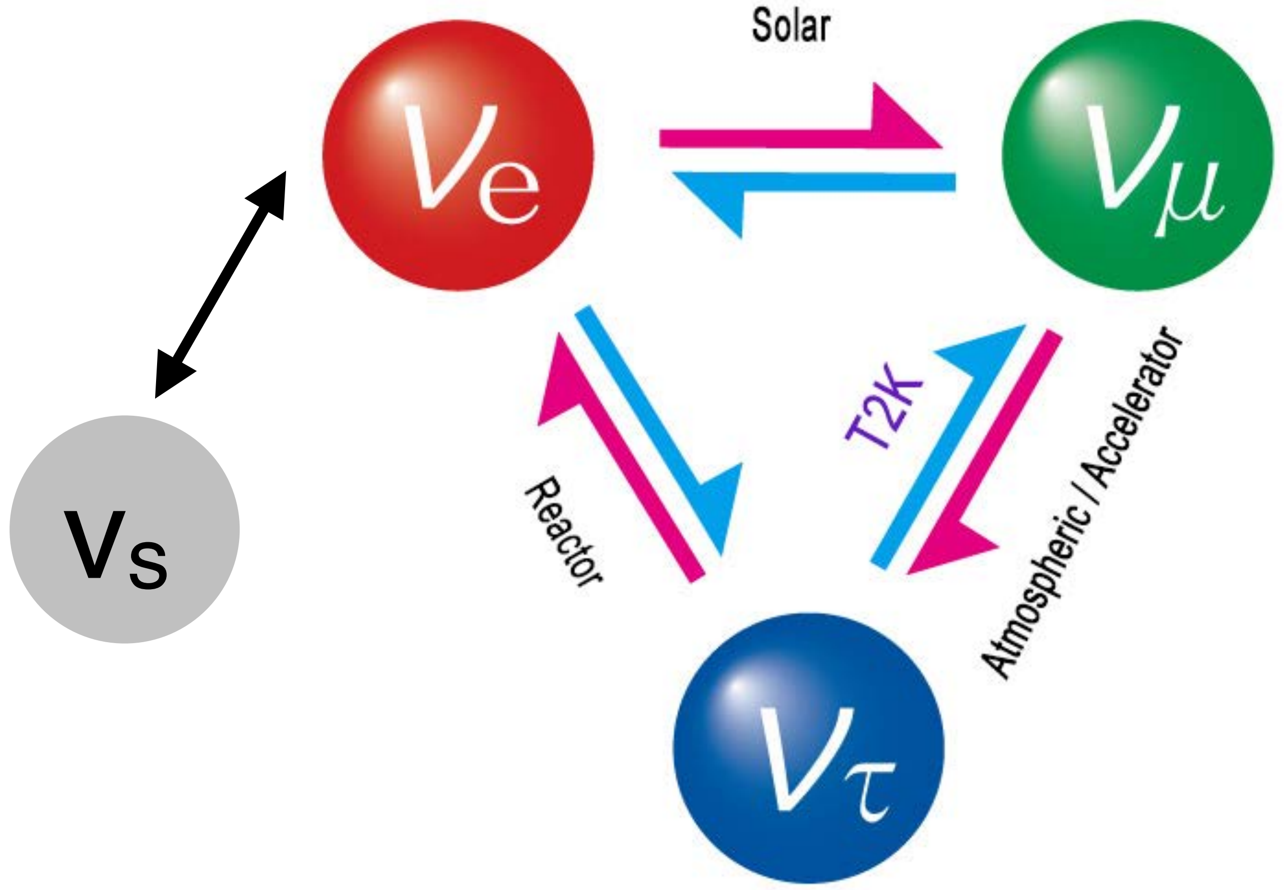
What is the ordering of neutrinos masses?

Is there CP-violation?

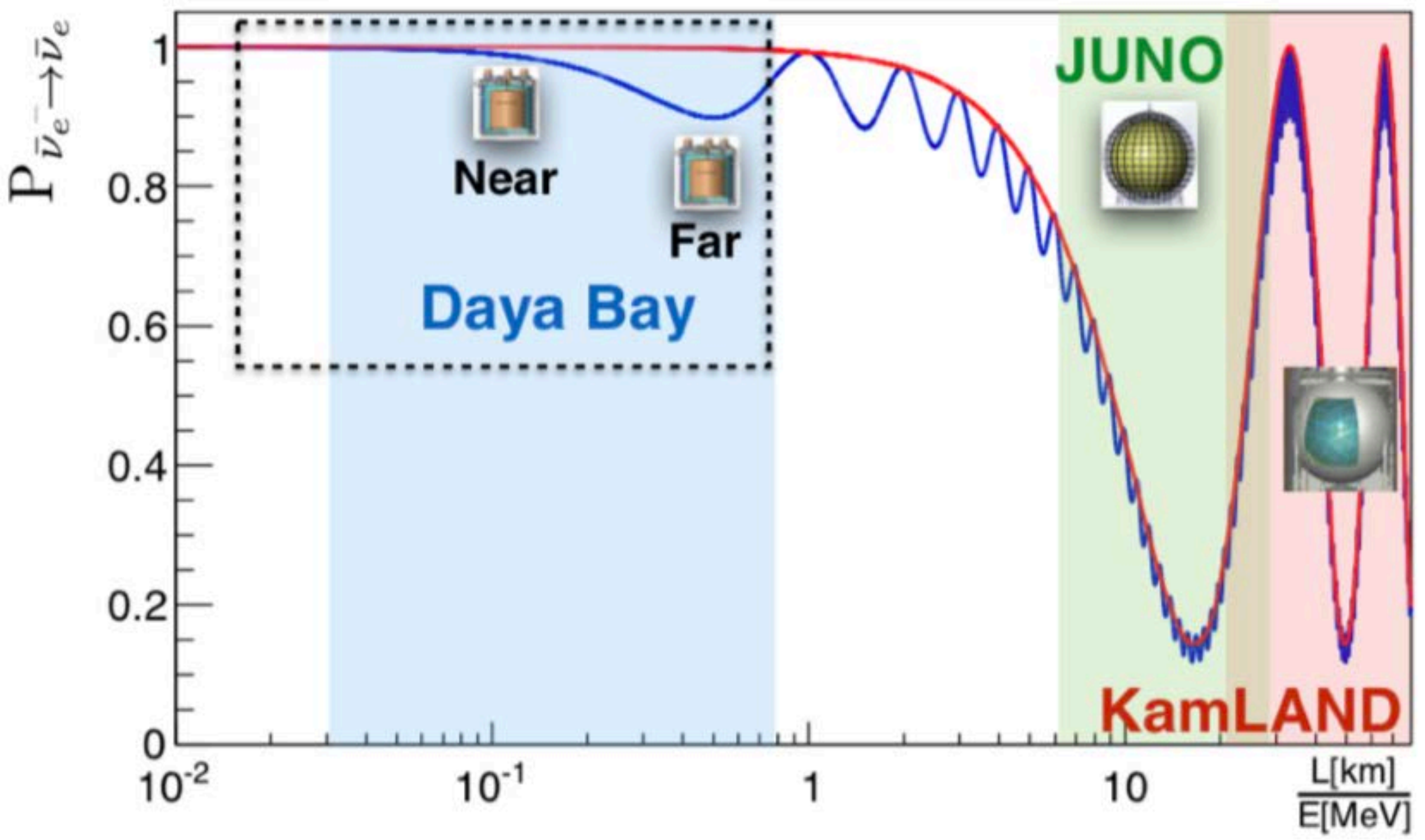
Is the standard picture 3 flavor paradigm correct?

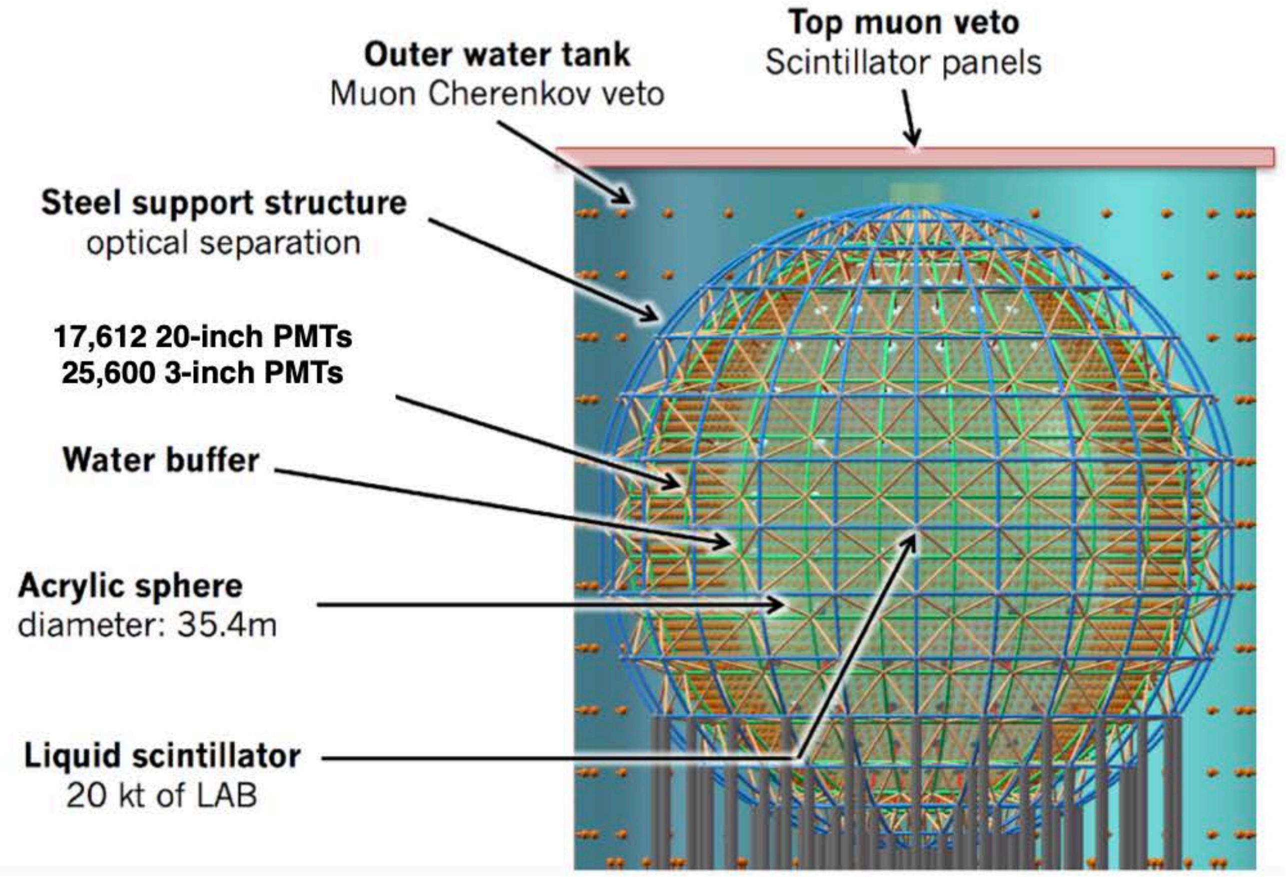
- Sterile neutrinos?
- Non-standard effects?



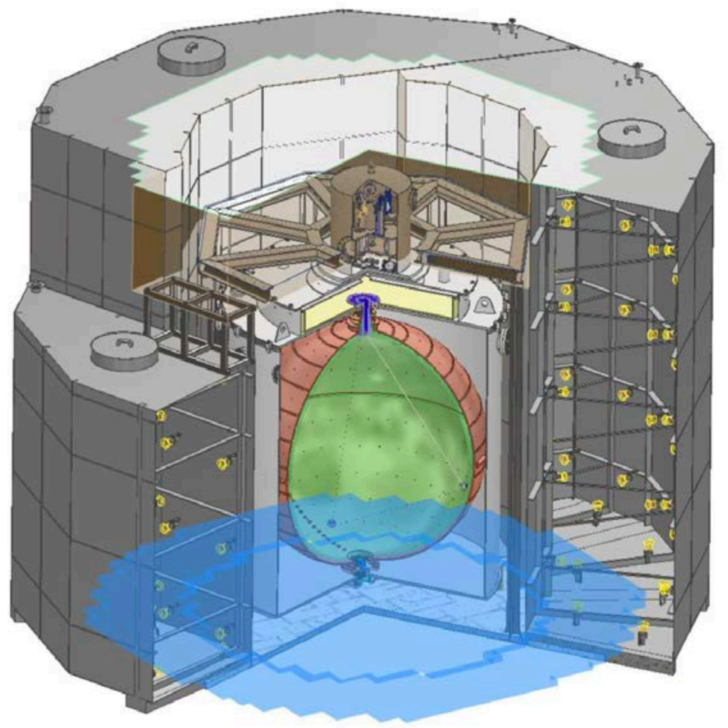


Jiangmen Underground Neutrino Observatory (JUNO)





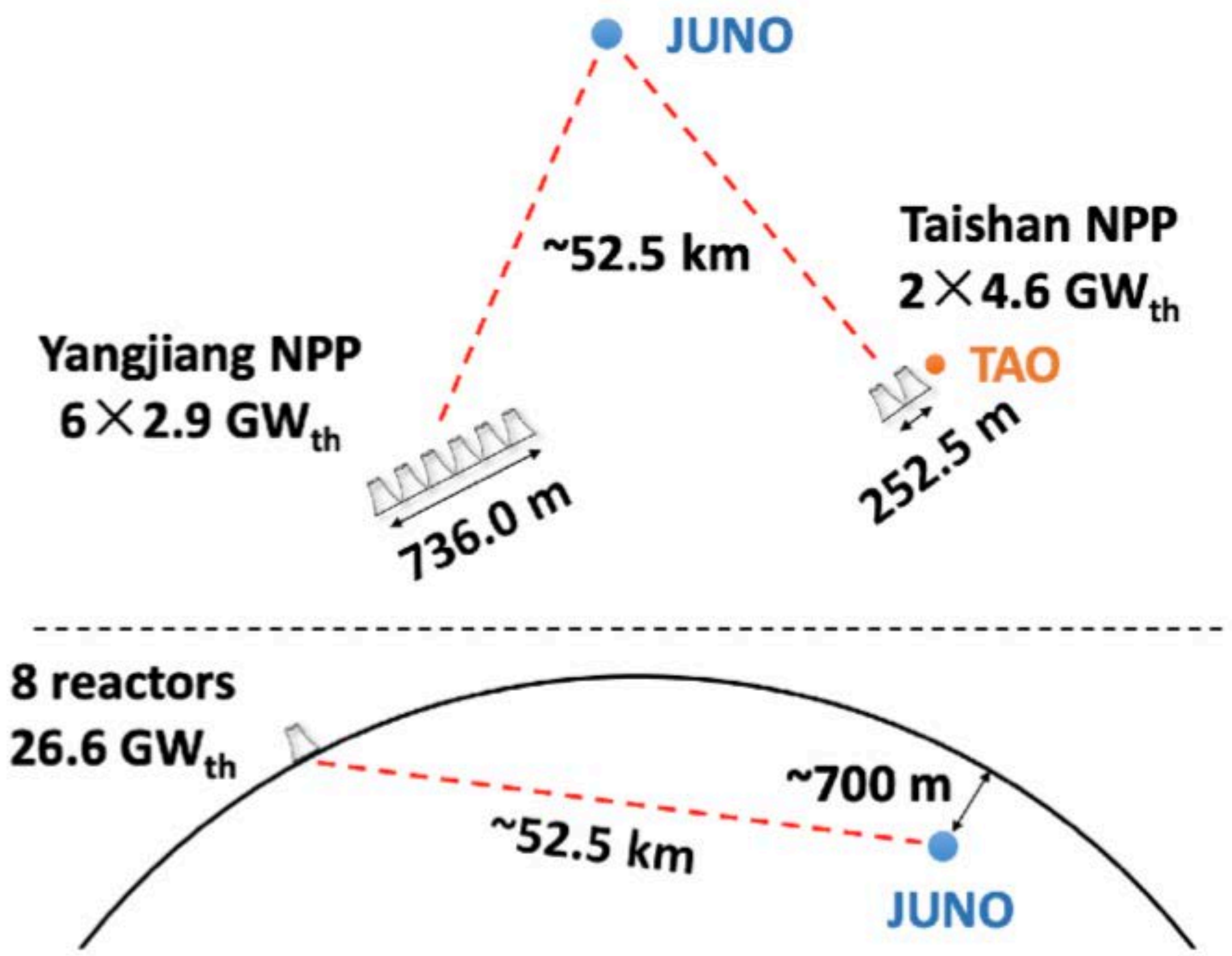
JUNO-Tao

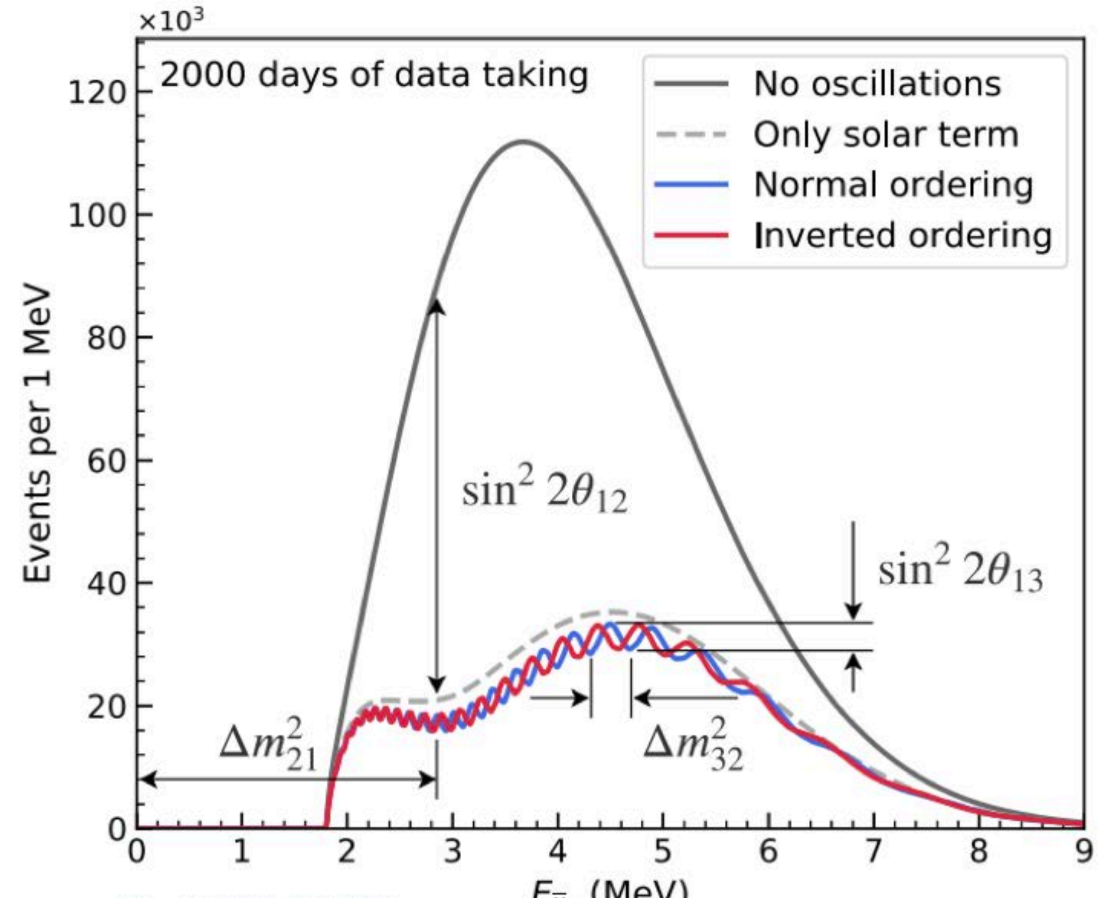


35.4 m diameter acrylic sphere filled with 20 kton of liquid scintillator (LS)

17,612 20” PMTs (LPMT) and 25,600 3” PMTs (SPMT)

- >75% photo-coverage
- ~30% detection efficiency (LPMT)



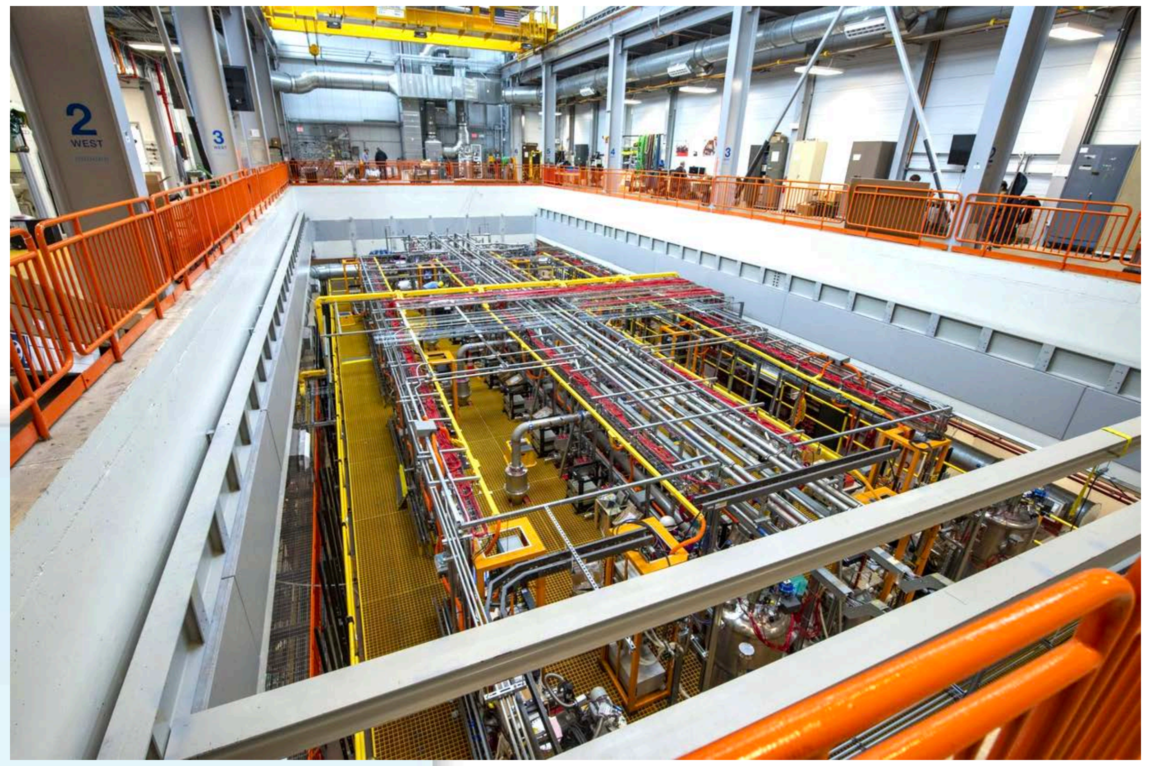


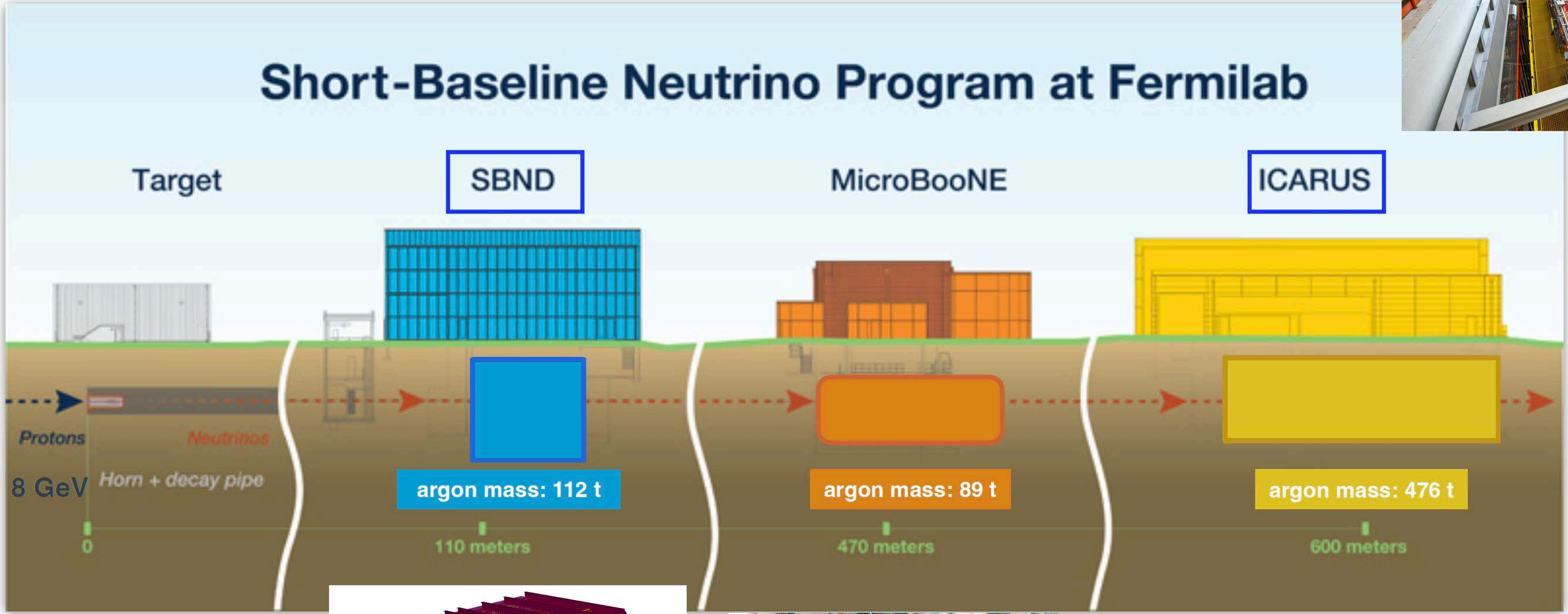
arXiv:2104.02565

JUNO Relative Uncertainty vs. Leading Experiments

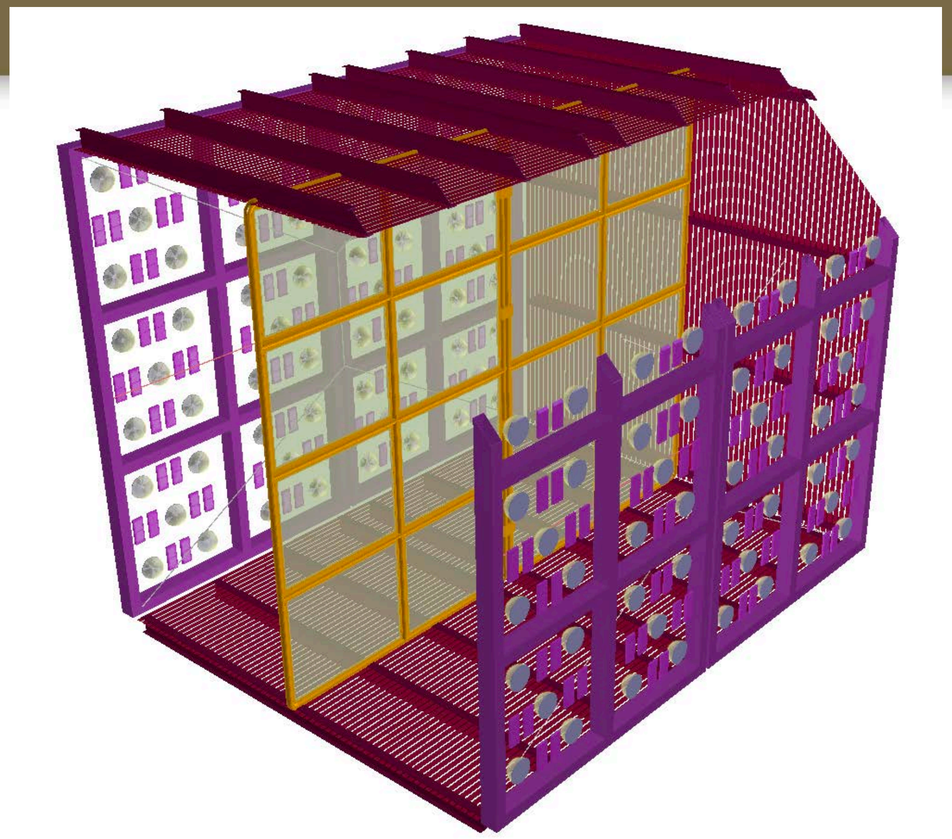
	Δm^2_{21}	Δm^2_{31}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
JUNO 100 days	0.8%	1%	1.9%	47.9%
JUNO 20 years	0.1%	0.2%	0.3%	7.3%
KamLAND	2.4%	-	-	-
T2K	-	2.6%	-	-
SNO+SK	-	-	4.5%	-
Daya Bay	-	-	-	3.4%

Short Baseline Neutrino Oscillation Searches





Booster Neutrino Beam (BNB)



Beam composition:

ν_μ (93.6%)

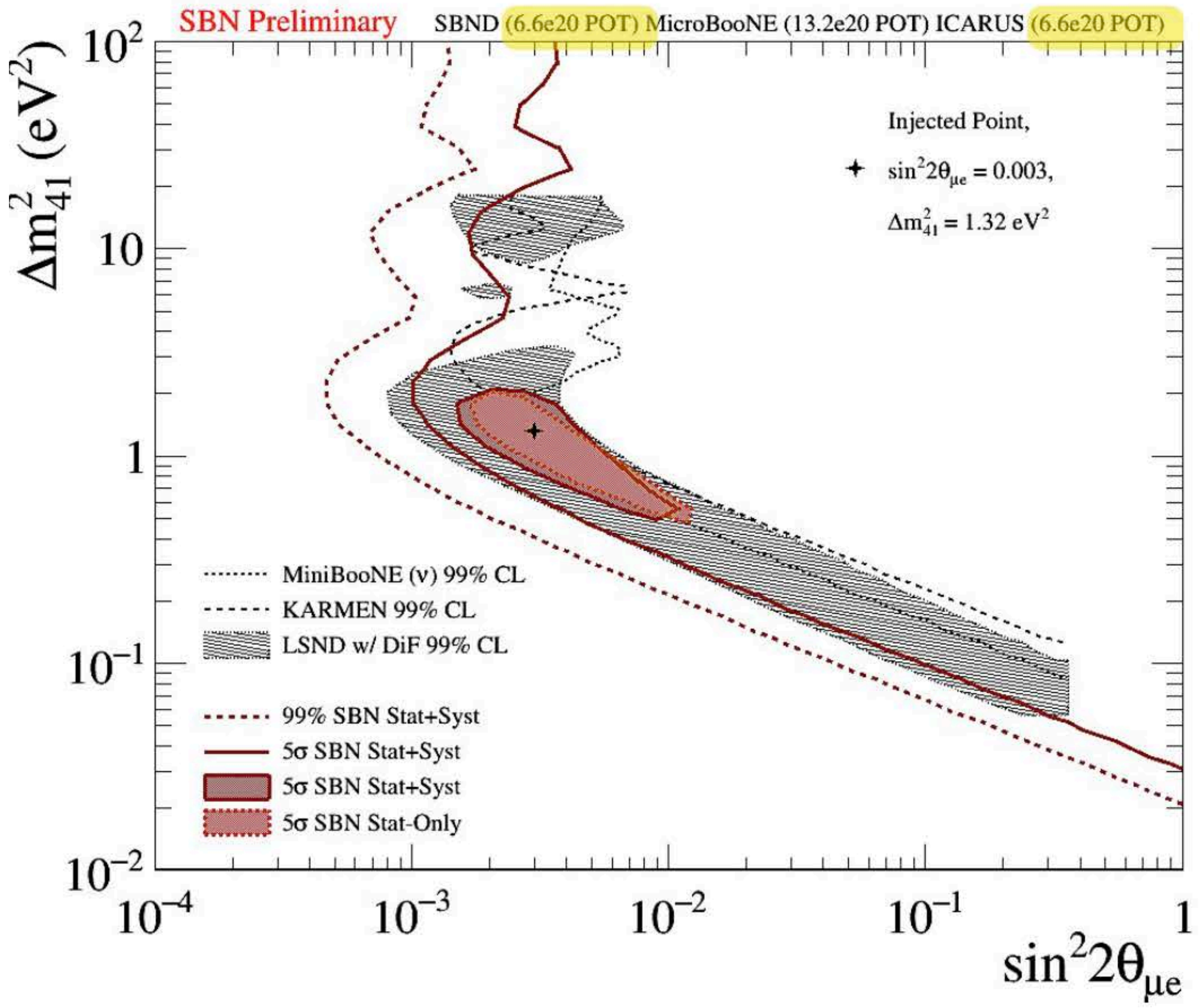
$\bar{\nu}_\mu$ (5.9%)

$\nu_e+\bar{\nu}_e$ (0.5%)

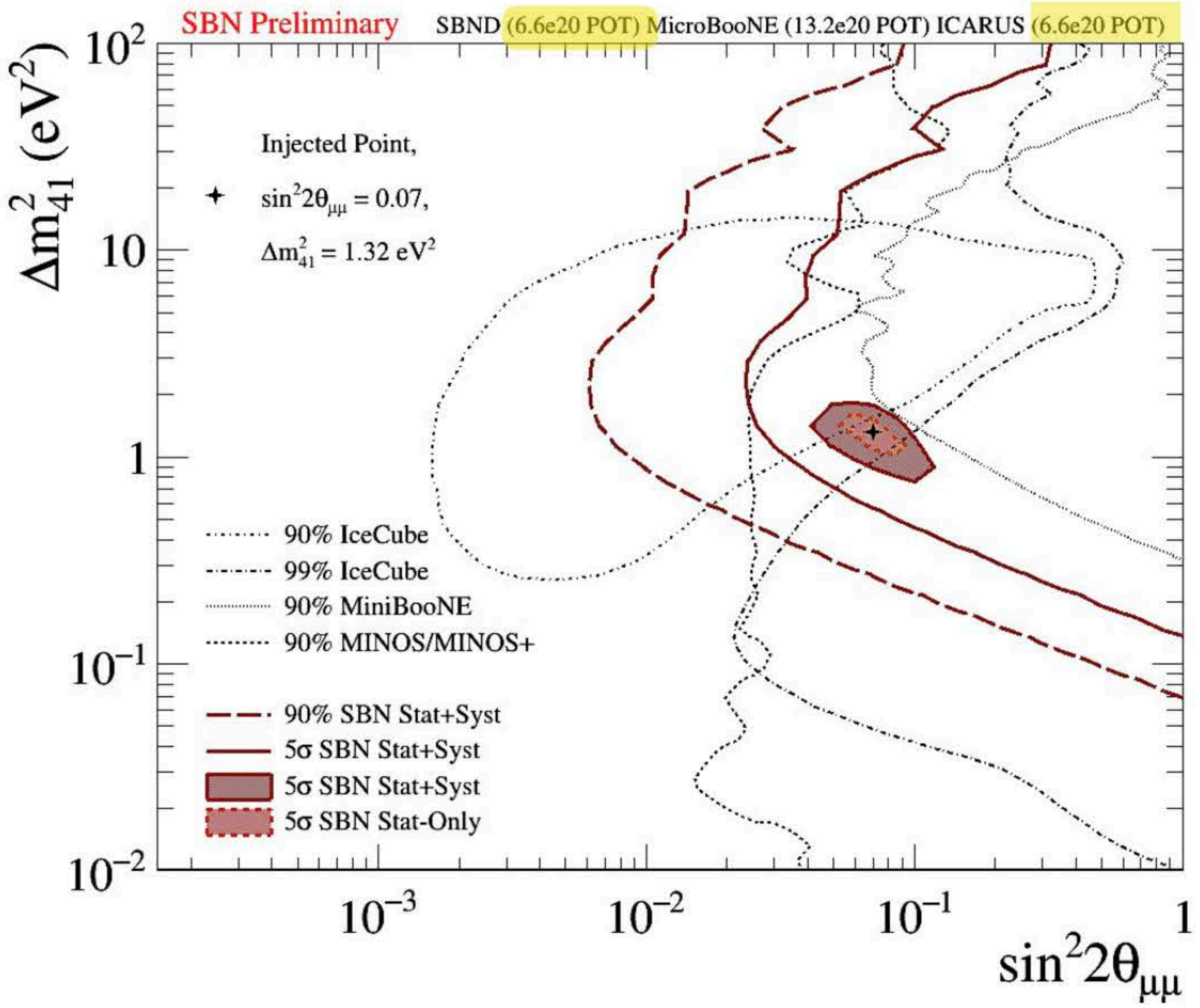
Mean ν_μ energy: ~0.8 GeV

Short Baseline Neutrino Oscillation Searches

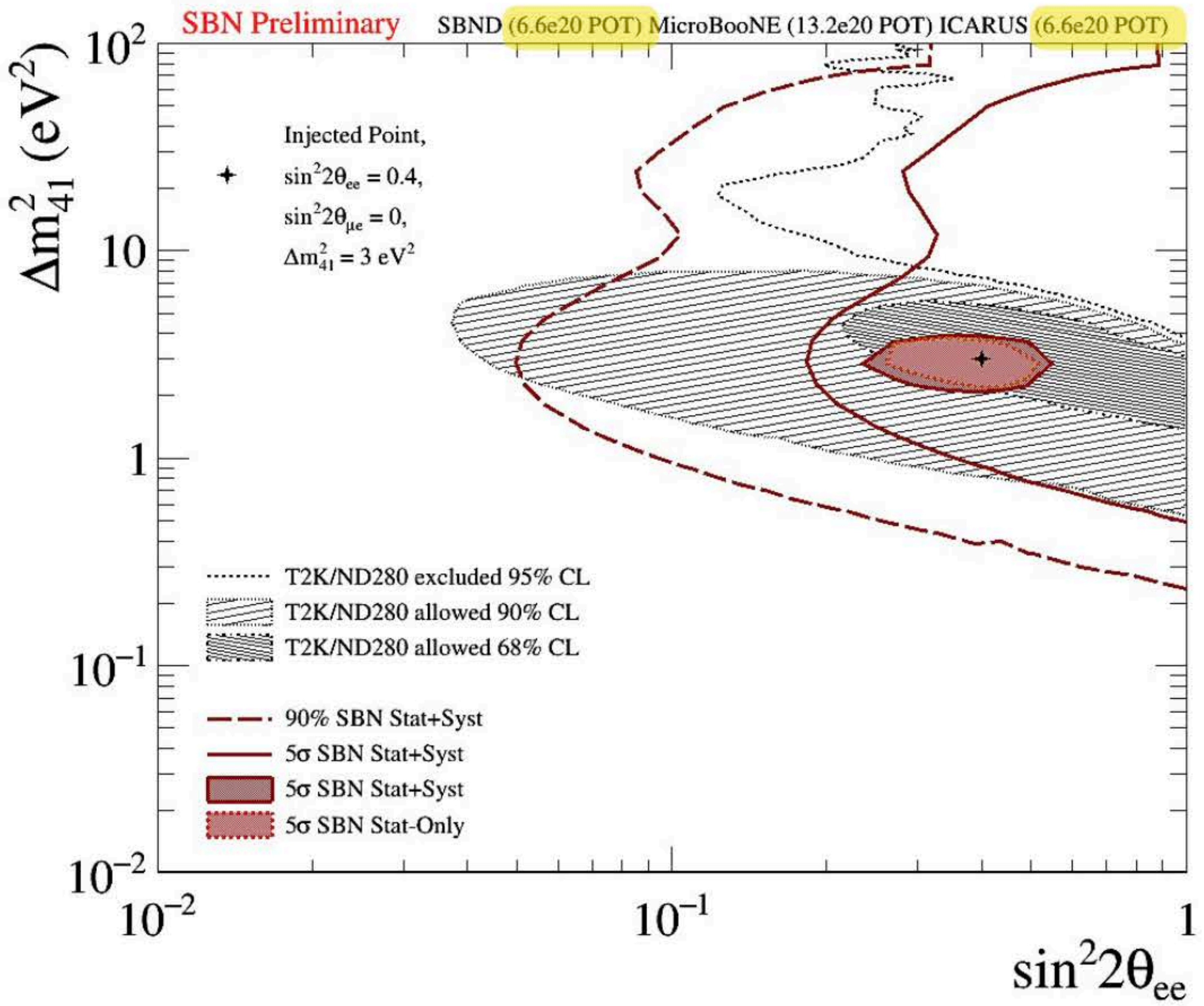
ν_e Appearance



ν_μ Disappearance



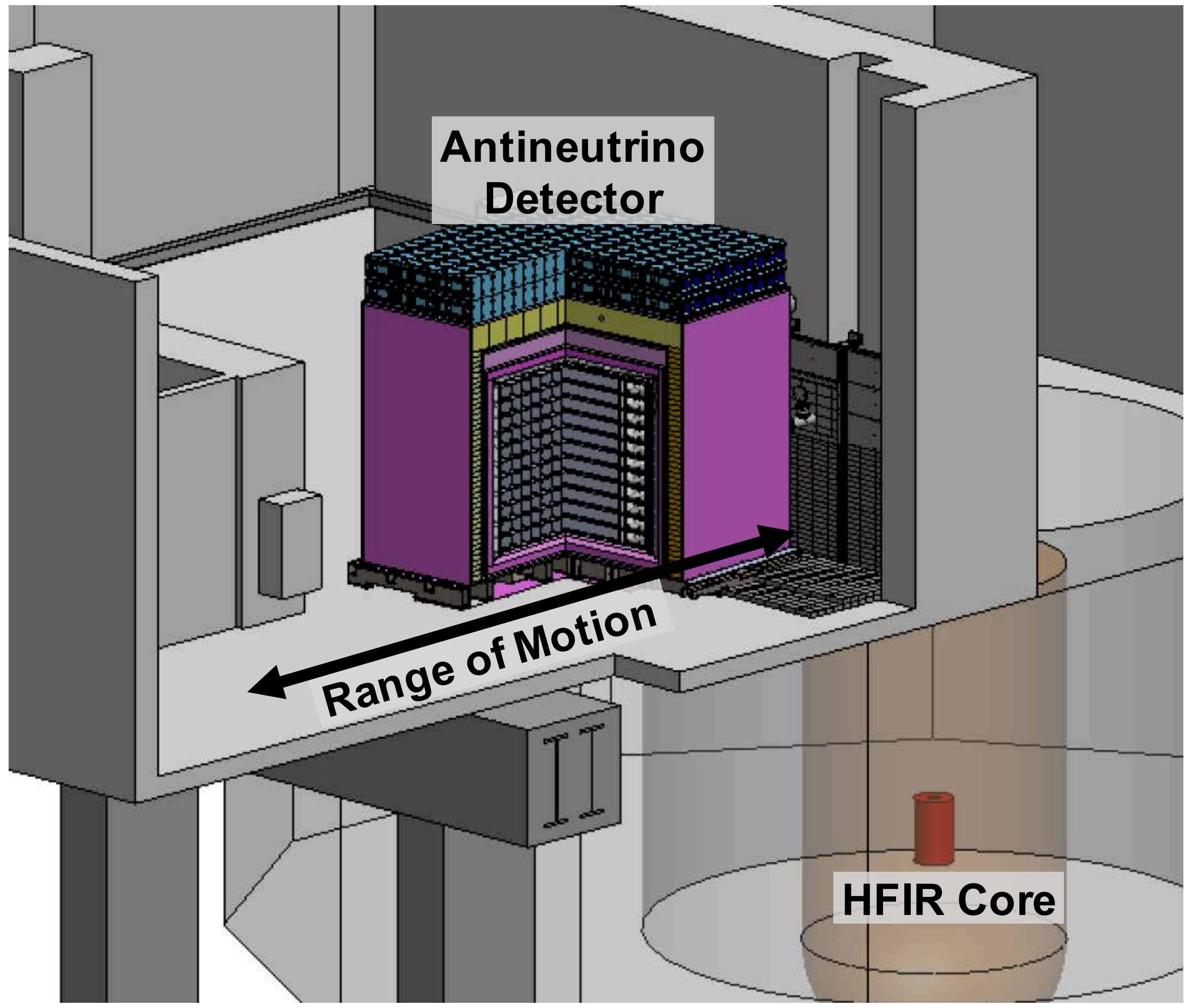
ν_e Disappearance



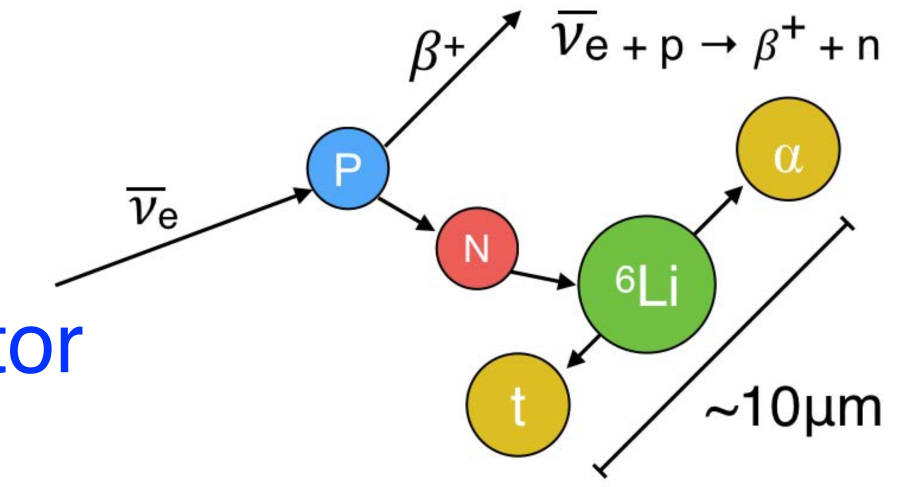
The SBN program tests the sterile neutrino hypothesis by covering the parameter regions allowed by past anomalies at **5σ significance**.

Complementary measurements in different modes:
important for interpretation in terms of **sterile neutrino oscillation**.

PROSPECT - Precision Oscillation and Spectrum Experiment



Segmented, ^{6}Li-loaded Detector



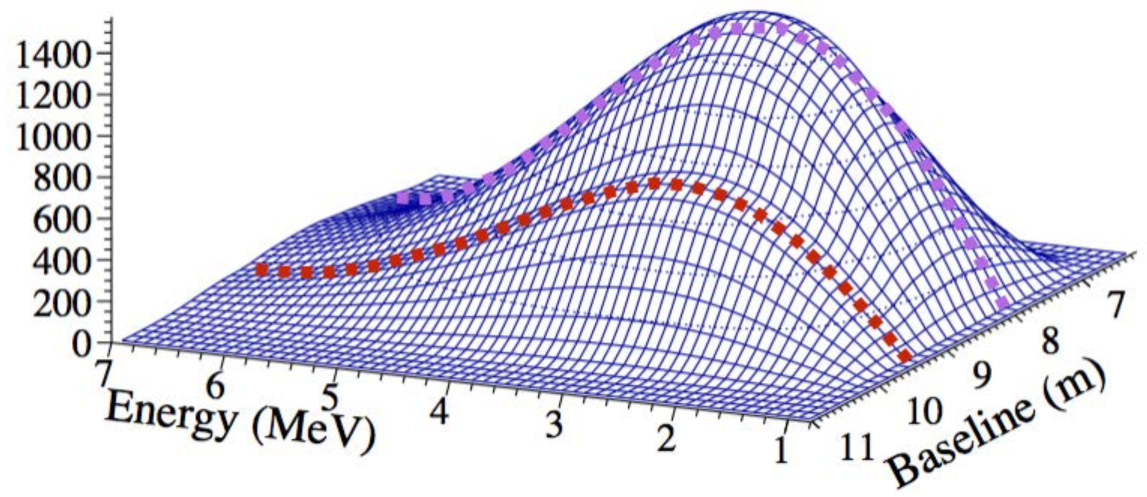
Search for short-baseline oscillation at <10m

Precision measurement of ^{235}U reactor $\overline{\nu}_e$ spectrum

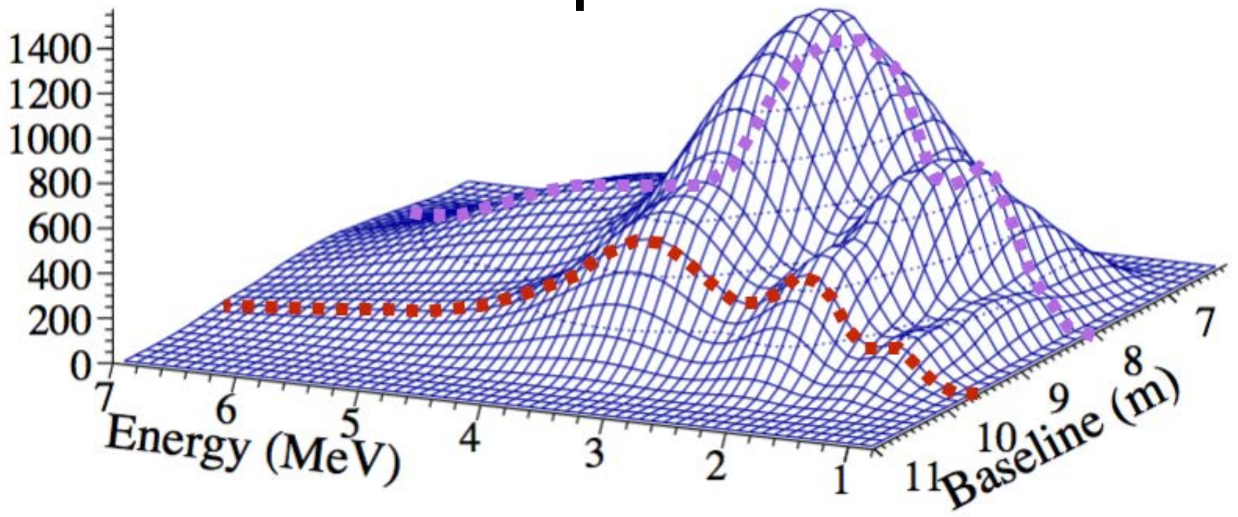
Relative Spectrum Measurement

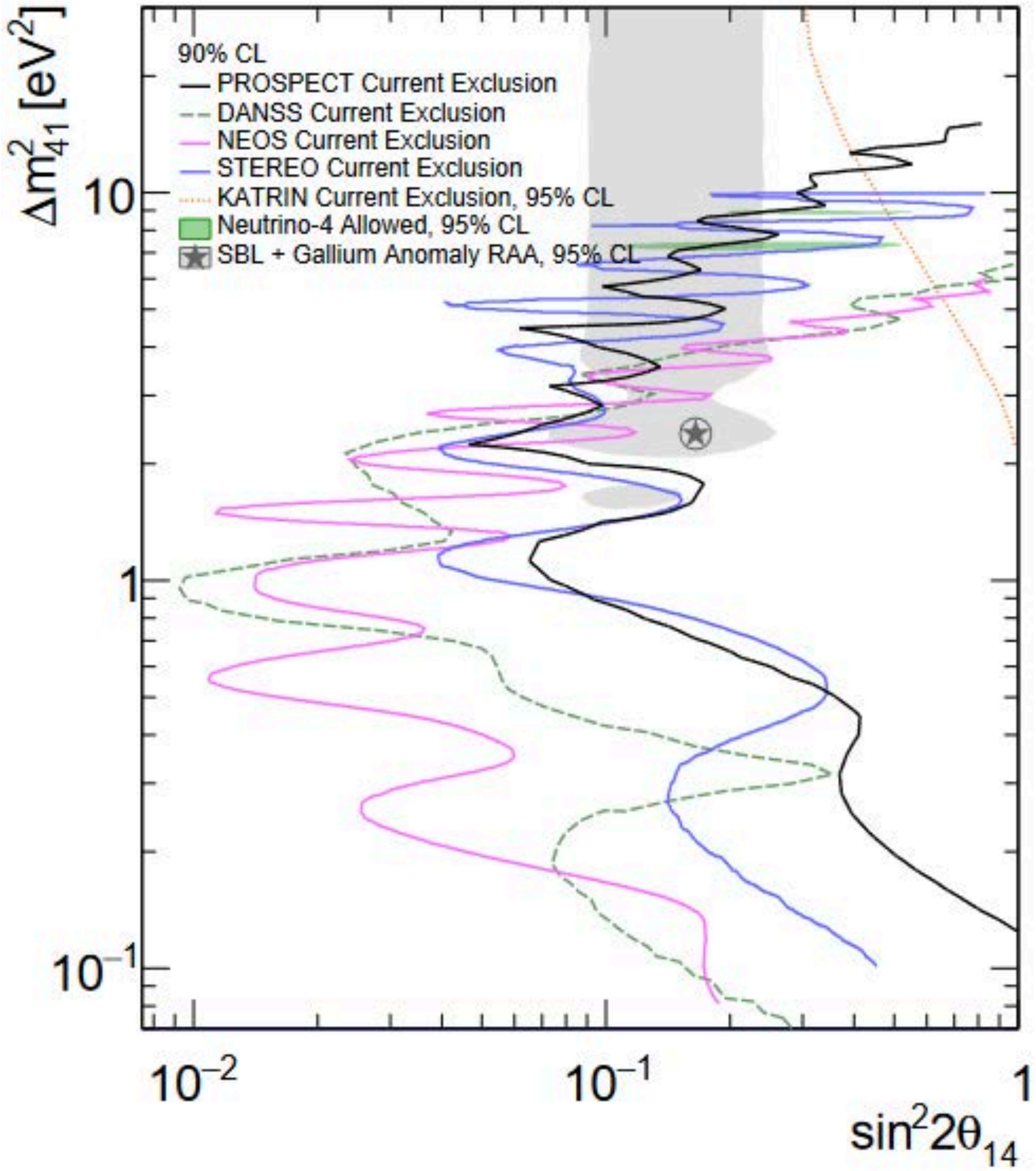
relative measurement of L/E and spectral shape distortions

unoscillated spectrum



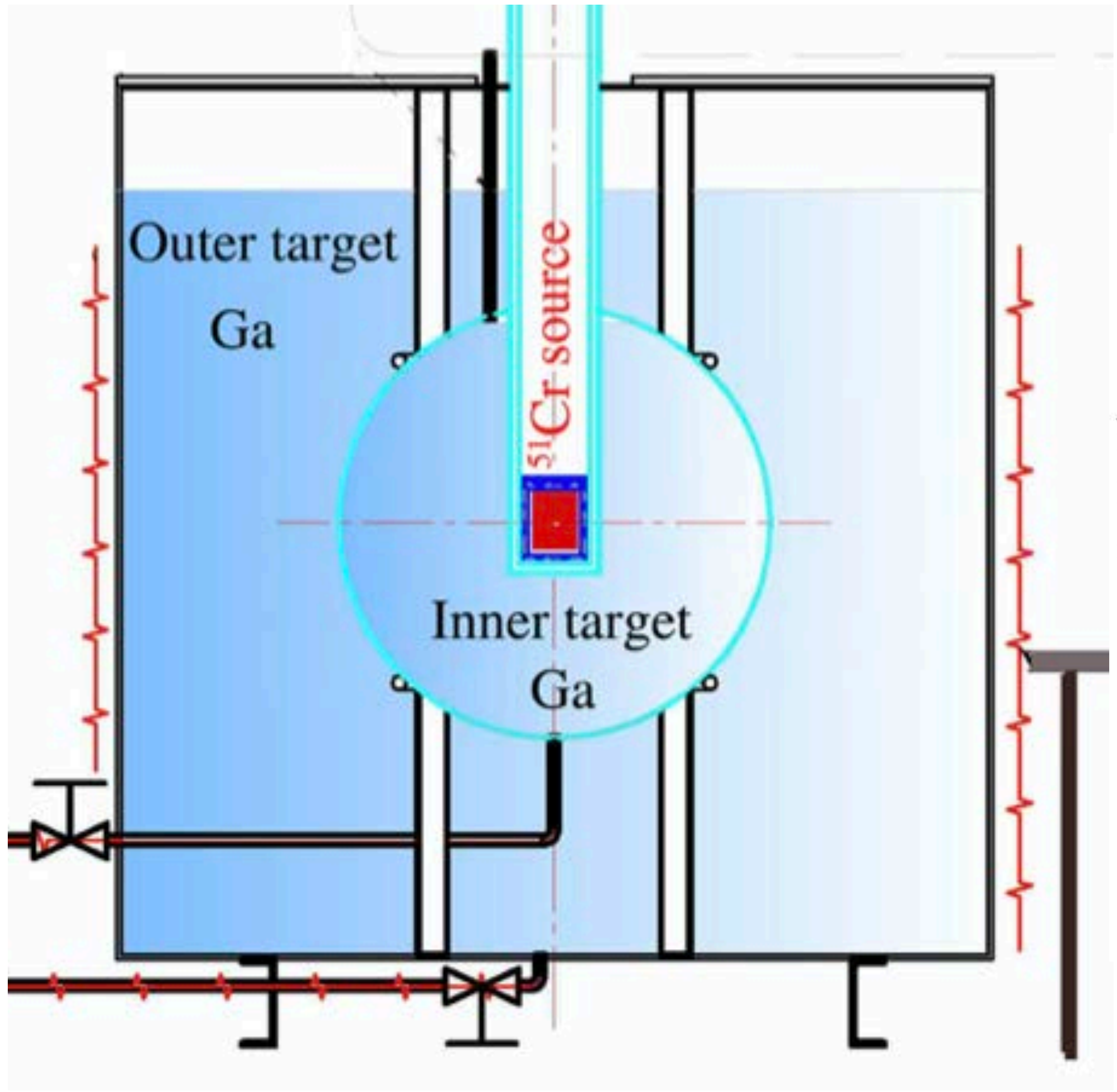
oscillated spectrum

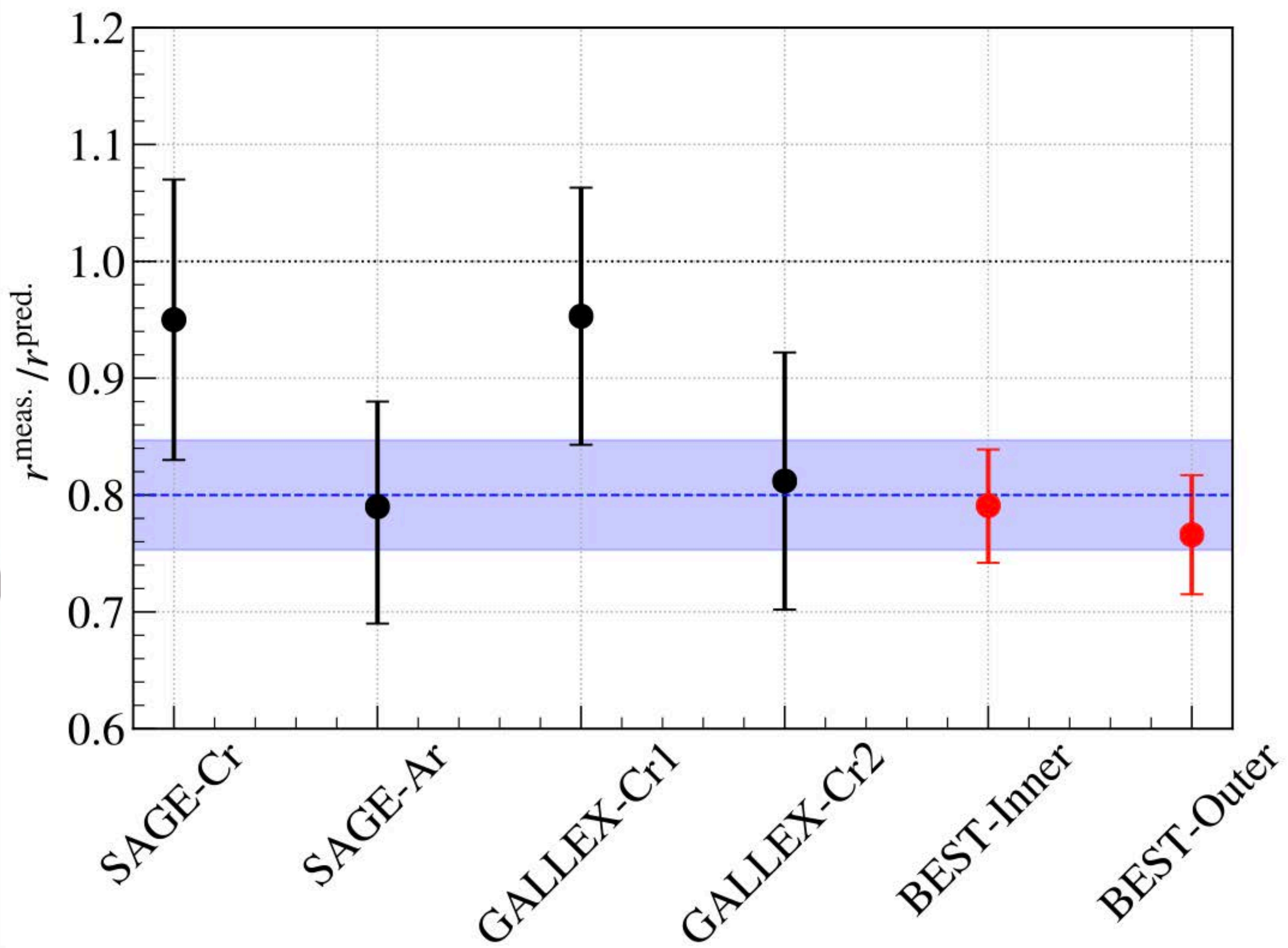


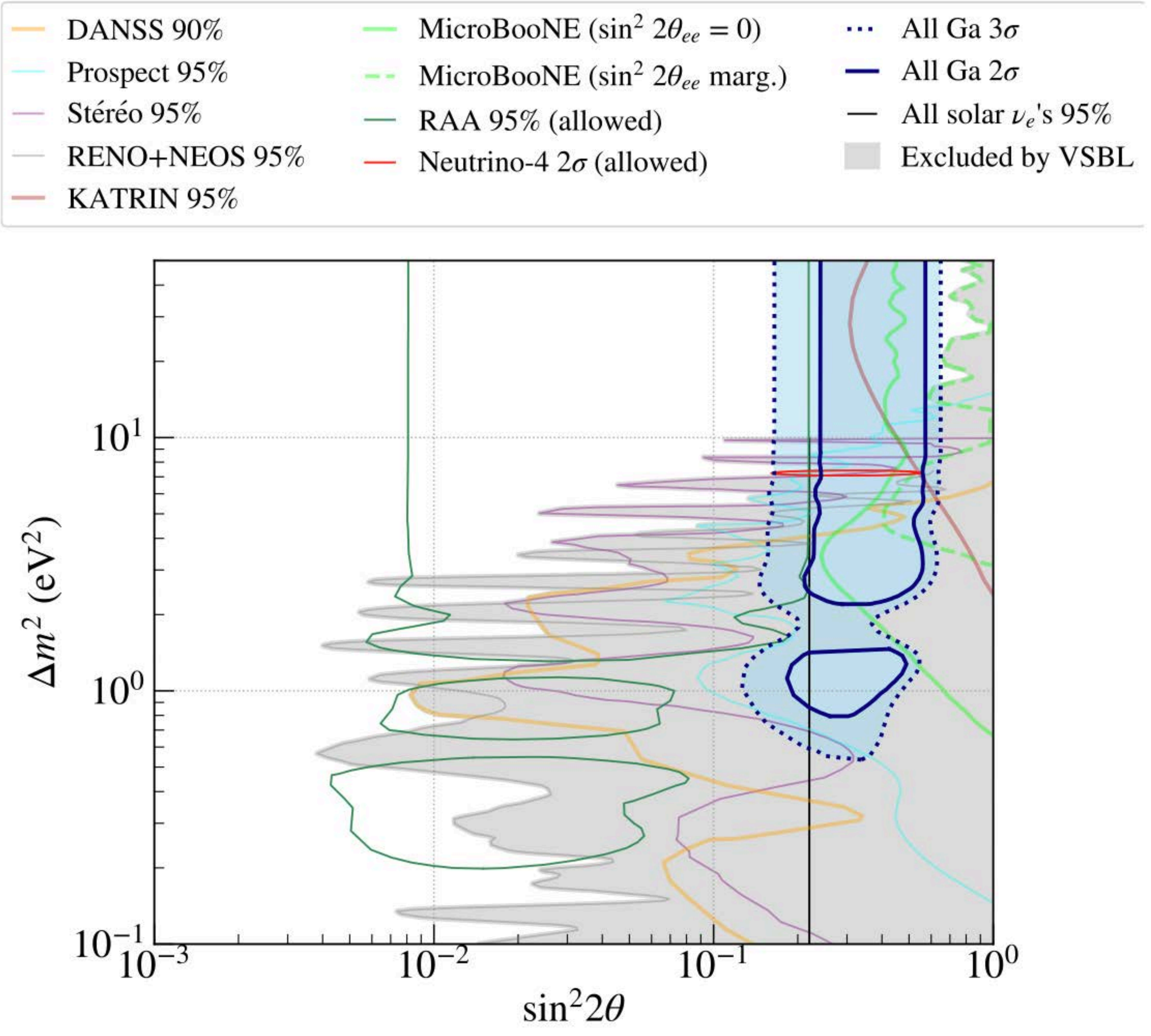


BEST Radiochemical Experiment

- 3.4 MCi ^{51}Cr source irradiates nested volumes of gallium
- $R_{in} = 0.791 \pm 0.05$ and $R_{out} = 0.766 \pm 0.05$
- significant deficit implies large mixing

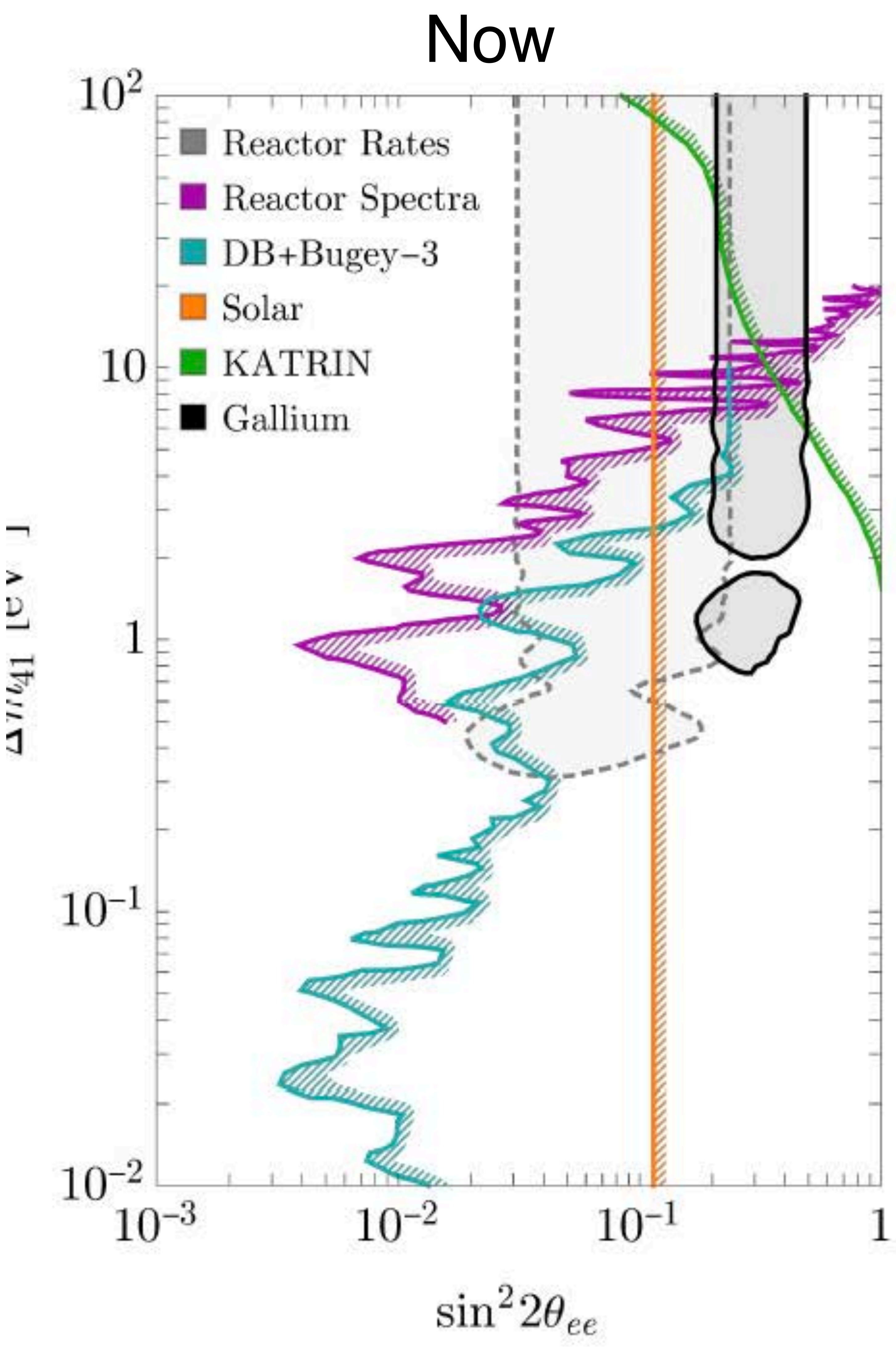


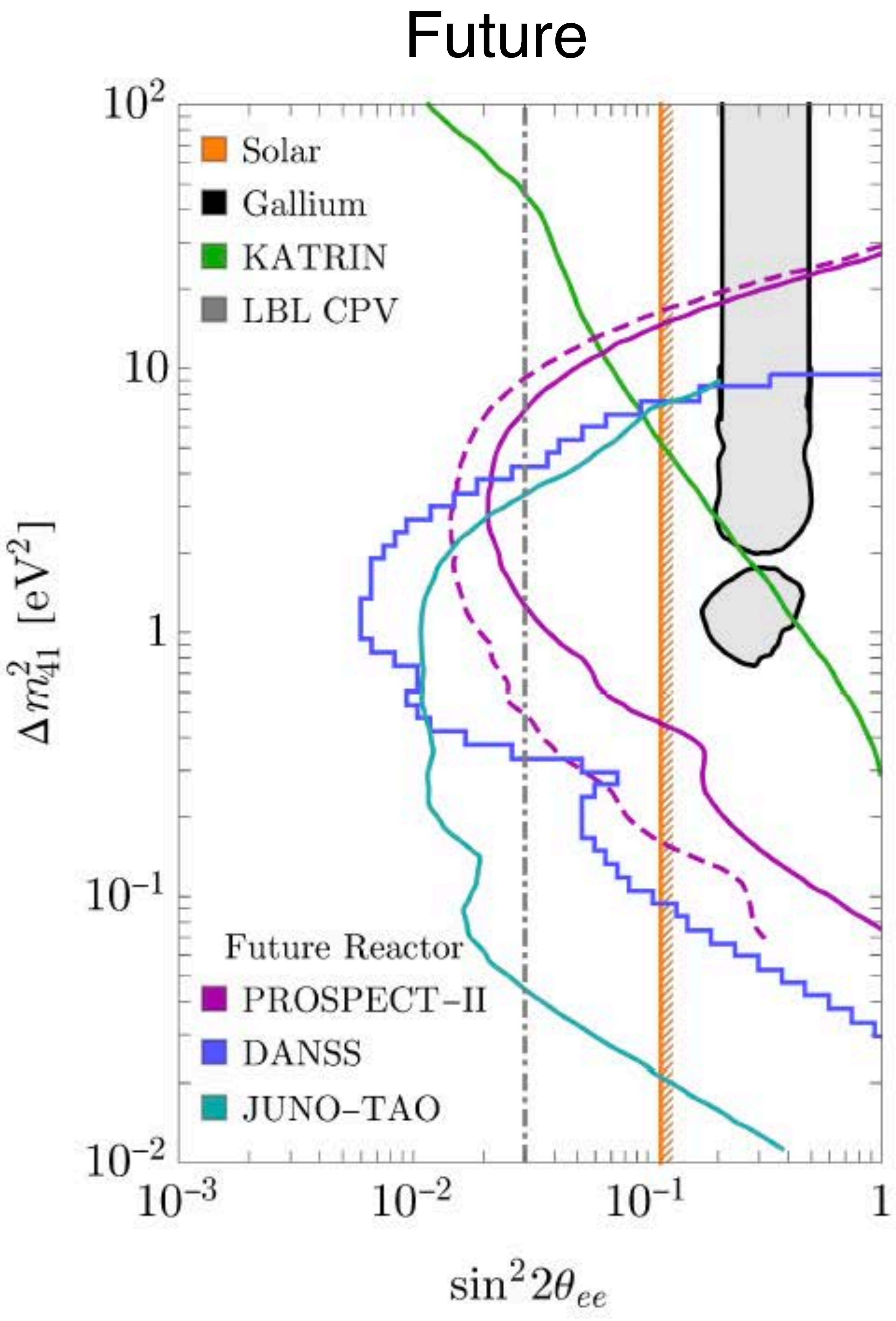


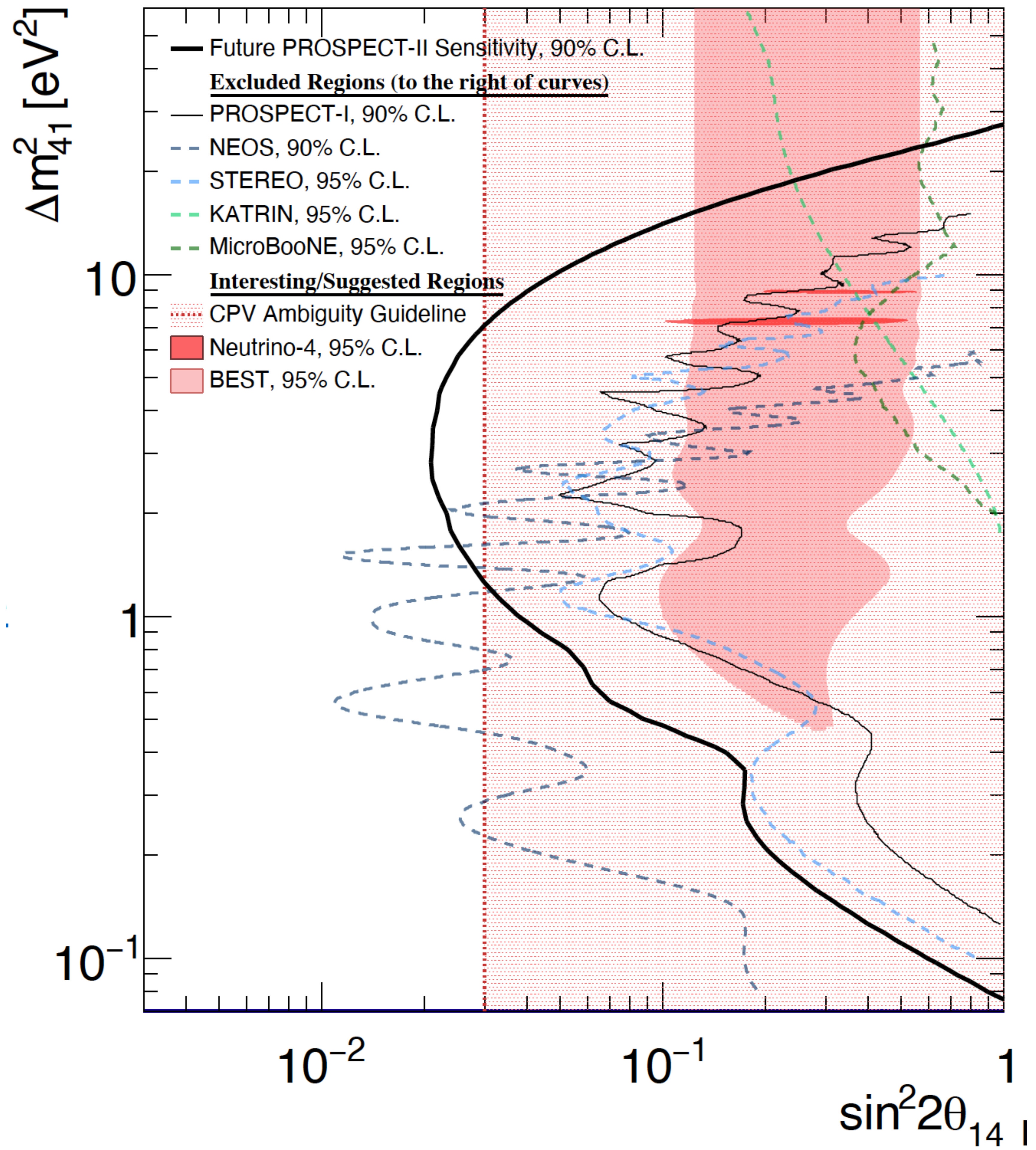


arXiv:2109.11482

Constraints on ν_e / $\overline{\nu_e}$ Disappearance







Long-Baseline Accelerator Experiments

Past — Current — Future

K2K
KEK to Kamioka
250 km, 5 kW

MINOS (+)
FNAL to Soudan
734 km, 400+ kW

CNGS
CERN to LNGS
730 km, 400 kW

NOνA
FNAL to Ash River
810 km, 400-700 kW

T2K (II)
J-PARC to Kamioka
295 km, 380-750 kW ➔>1 MW

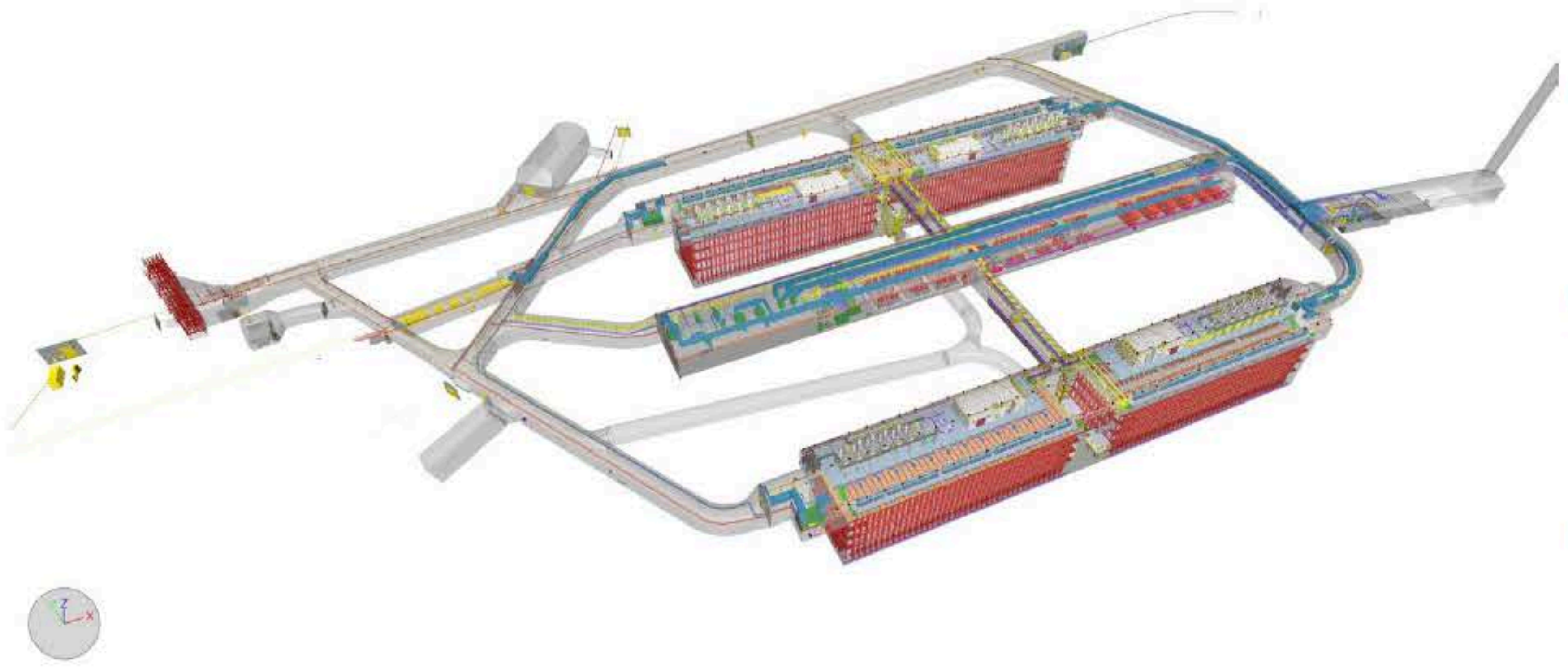
LBNF/DUNE
FNAL to Homestake
1300 km, 1.2 MW (➔2+ MW)

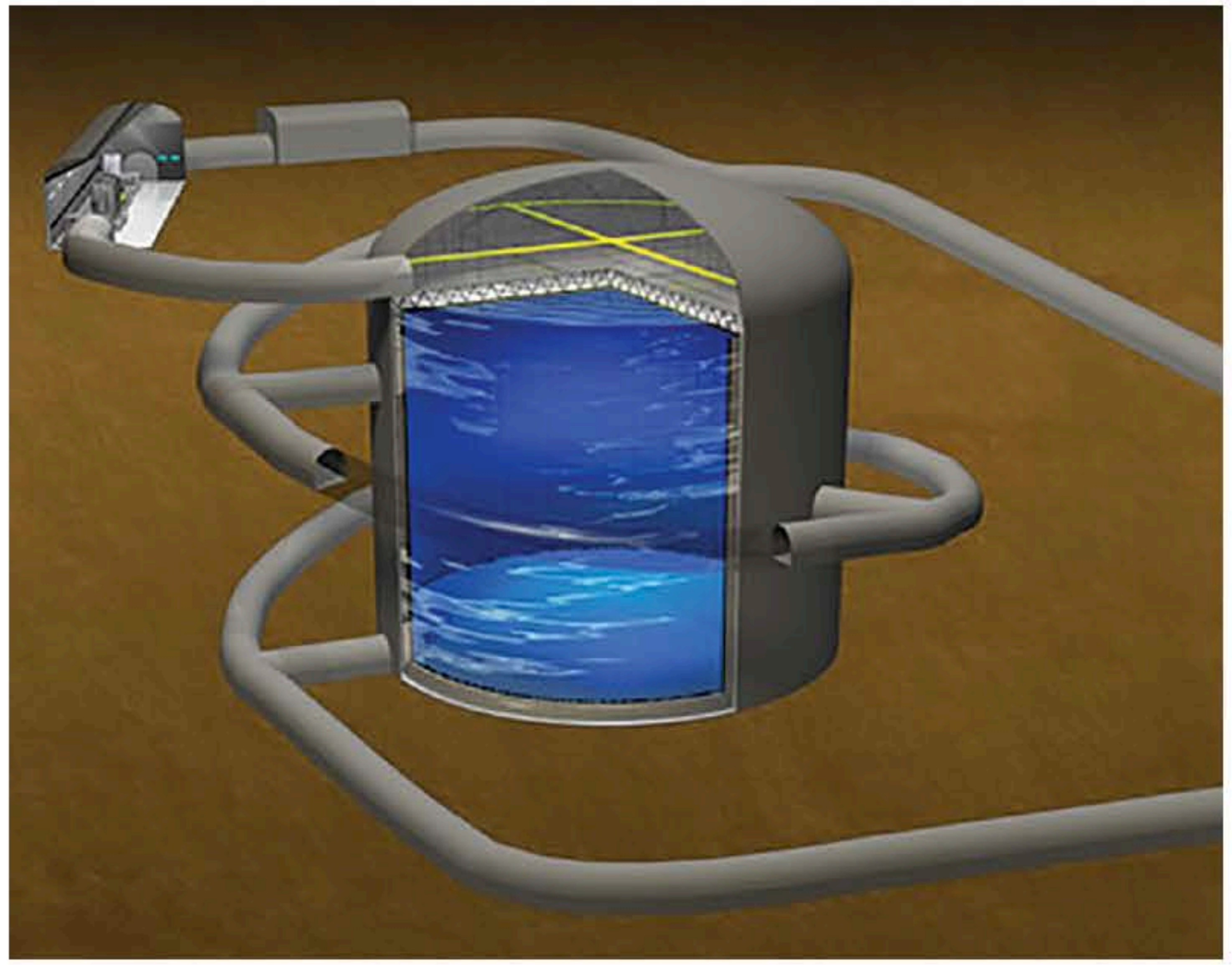
Hyper-K
J-PARC to Kamioka
295 km, 750 kW
(➔1.3 MW)



K. Scholberg

DUNE and Hyper-K





DUNE

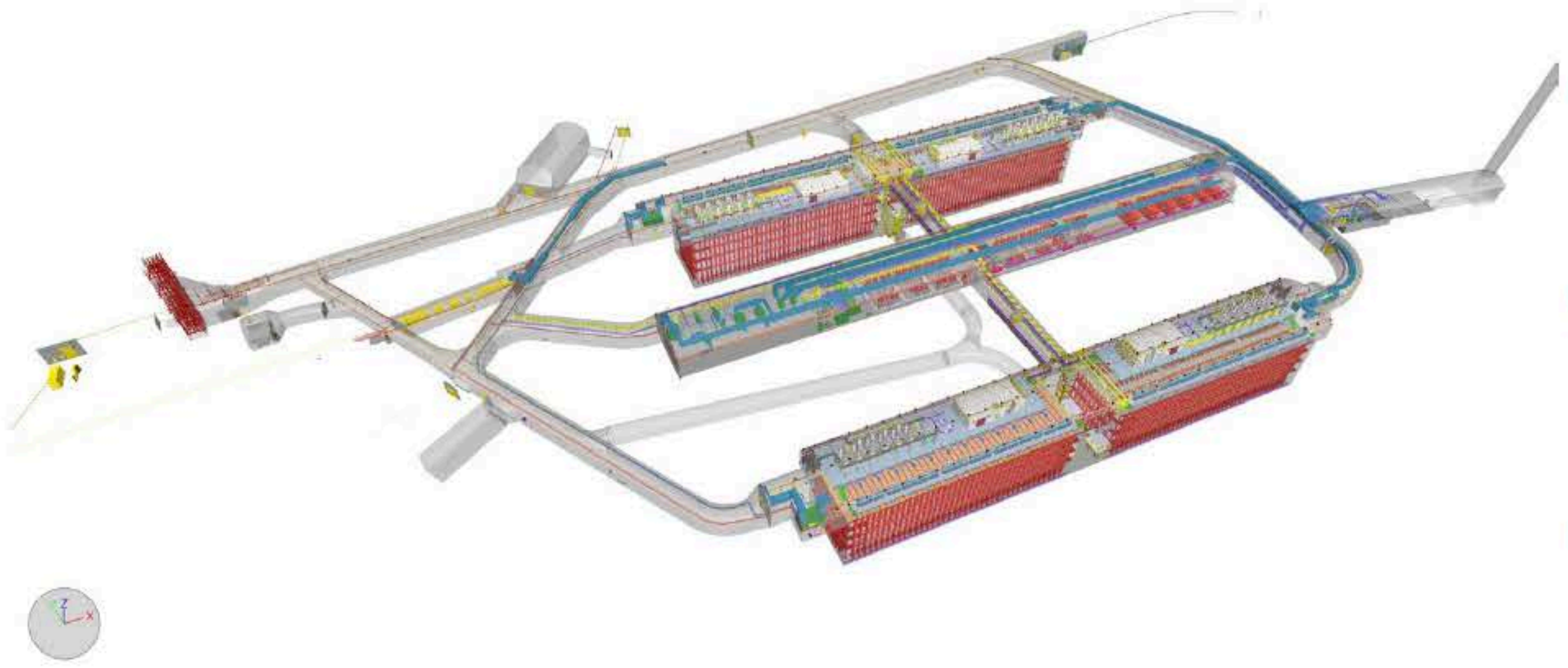
- Very long baseline → large matter effect → unambiguous mass ordering and CPV
- Broadband neutrino beam → high statistics over full oscillation period
- Reconstruct E_ν over broad range → imaging + calorimetry → LArTPC technology
- Highly-capable near detector to constrain systematic uncertainties

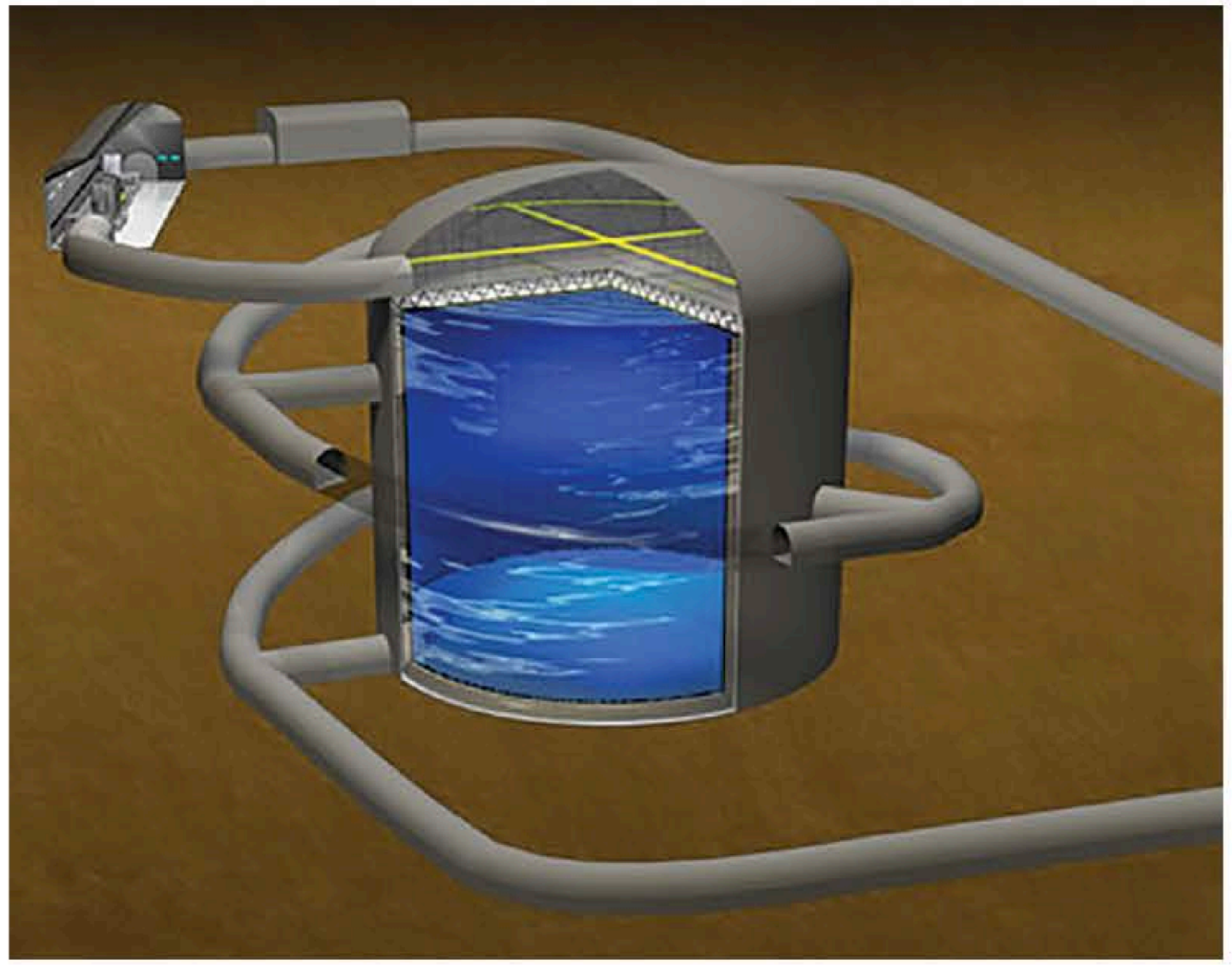
Hyper-K

- Shorter baseline → small matter effect
- Off-axis location & narrowband beam → very, very high statistics at oscillation maximum, less feed-down
- Lower energy and mostly CCQE → very large water Cherenkov detector
- Highly-capable near detector to constrain systematic uncertainties

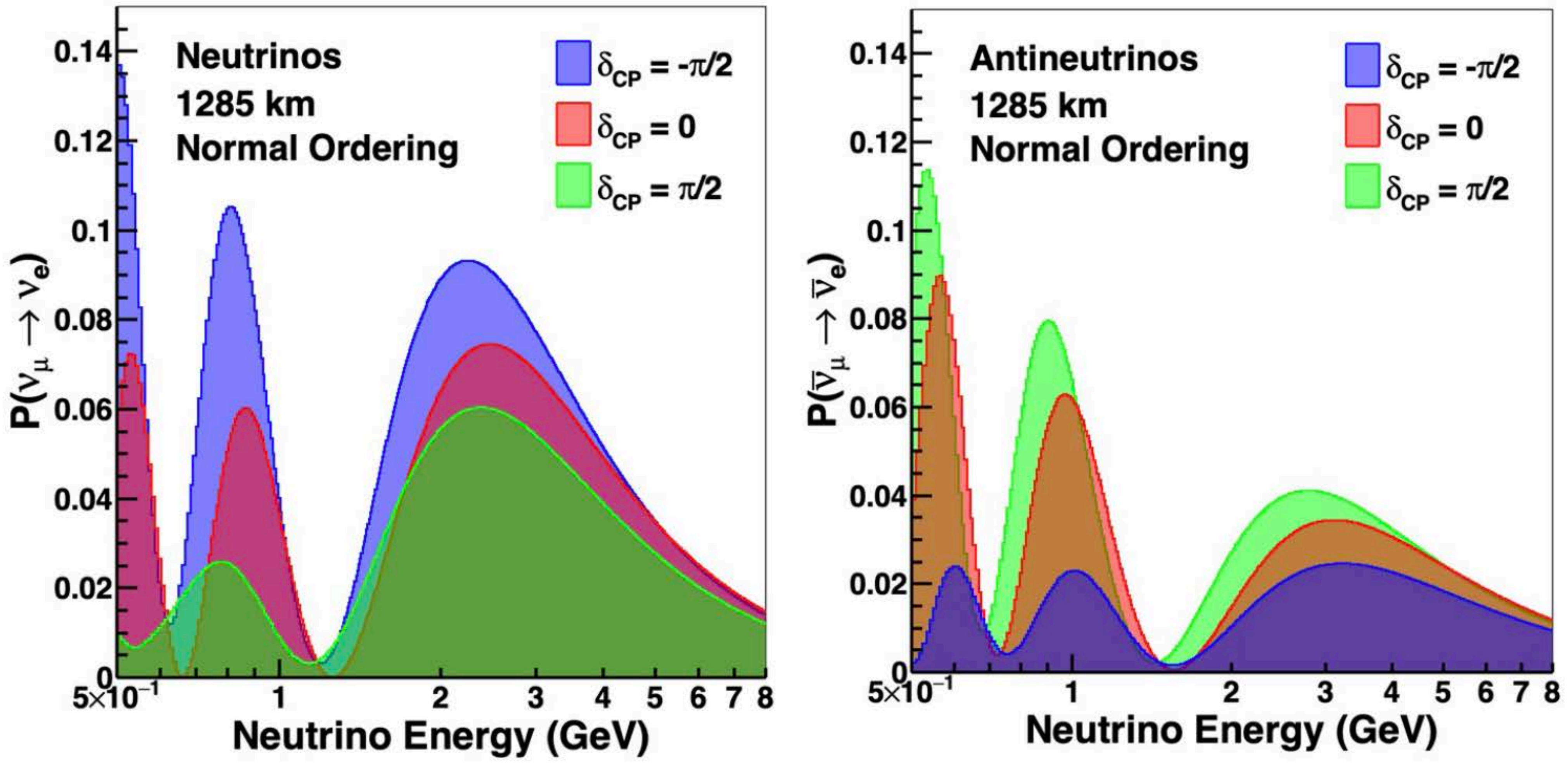
C. Marshall

DUNE and Hyper-K

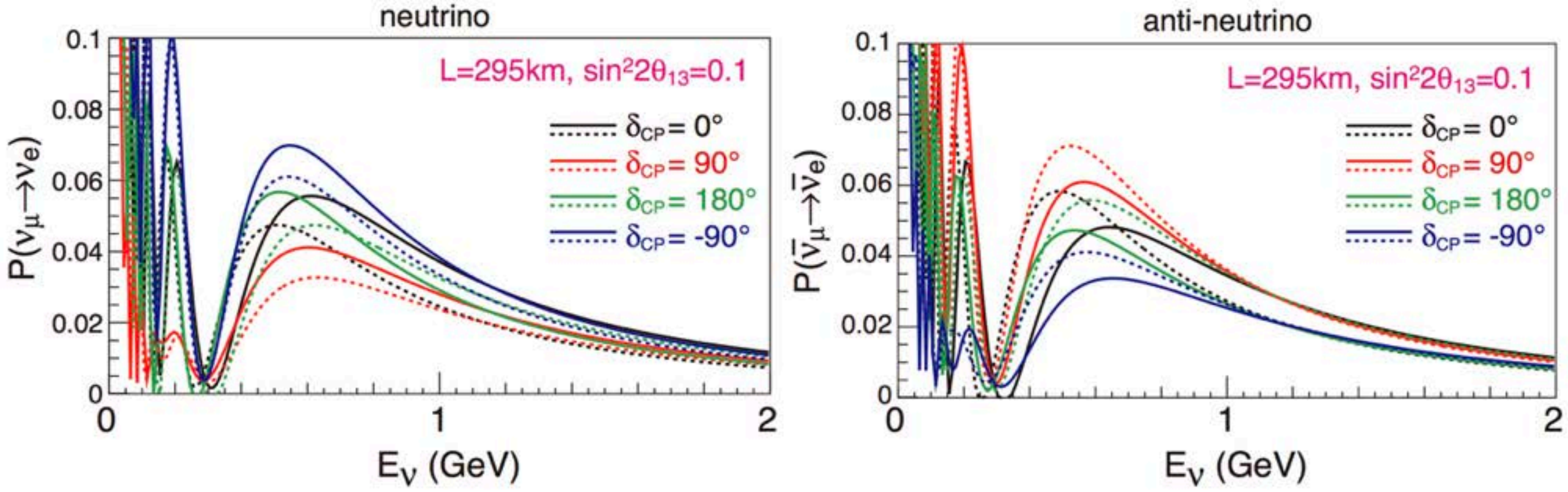




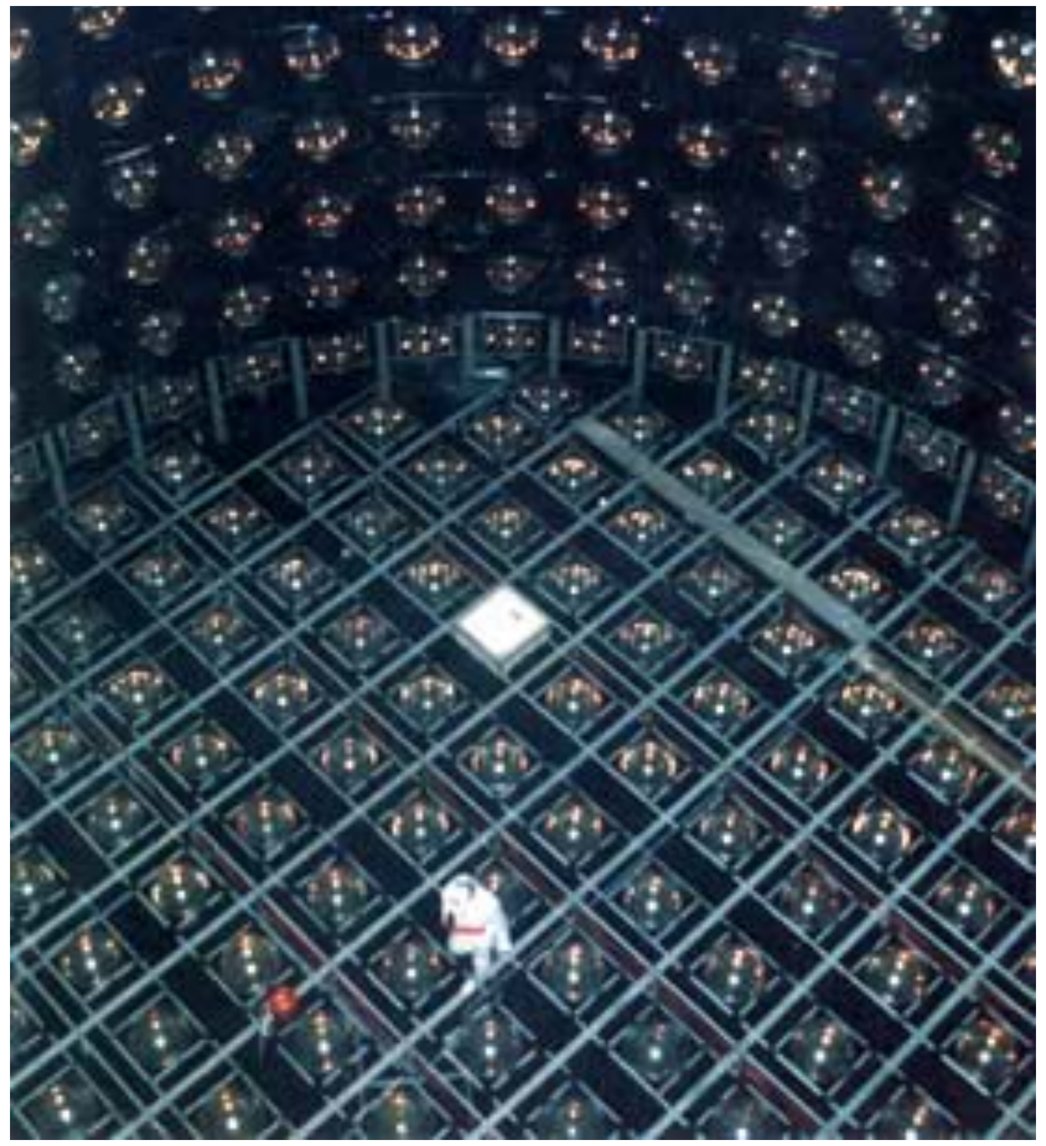
DUNE



Hyper-K



THREE GENERATIONS OF WATER CHERENKOV DETECTOR IN KAMIOKA

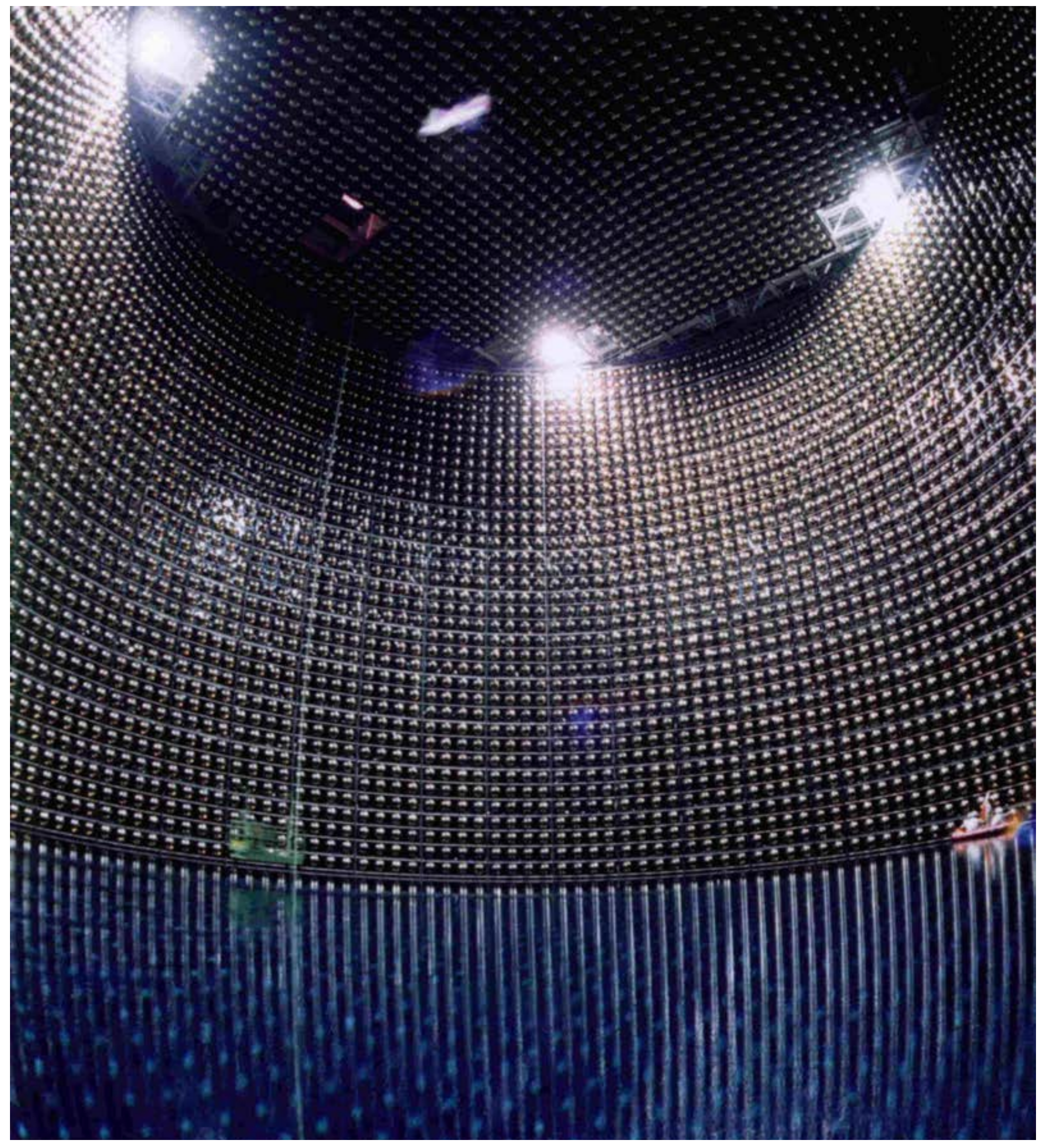


Kamiokande

(1983-1996)

- Atmospheric and solar neutrino “anomaly”
- Supernova 1987A

Birth of neutrino astrophysics

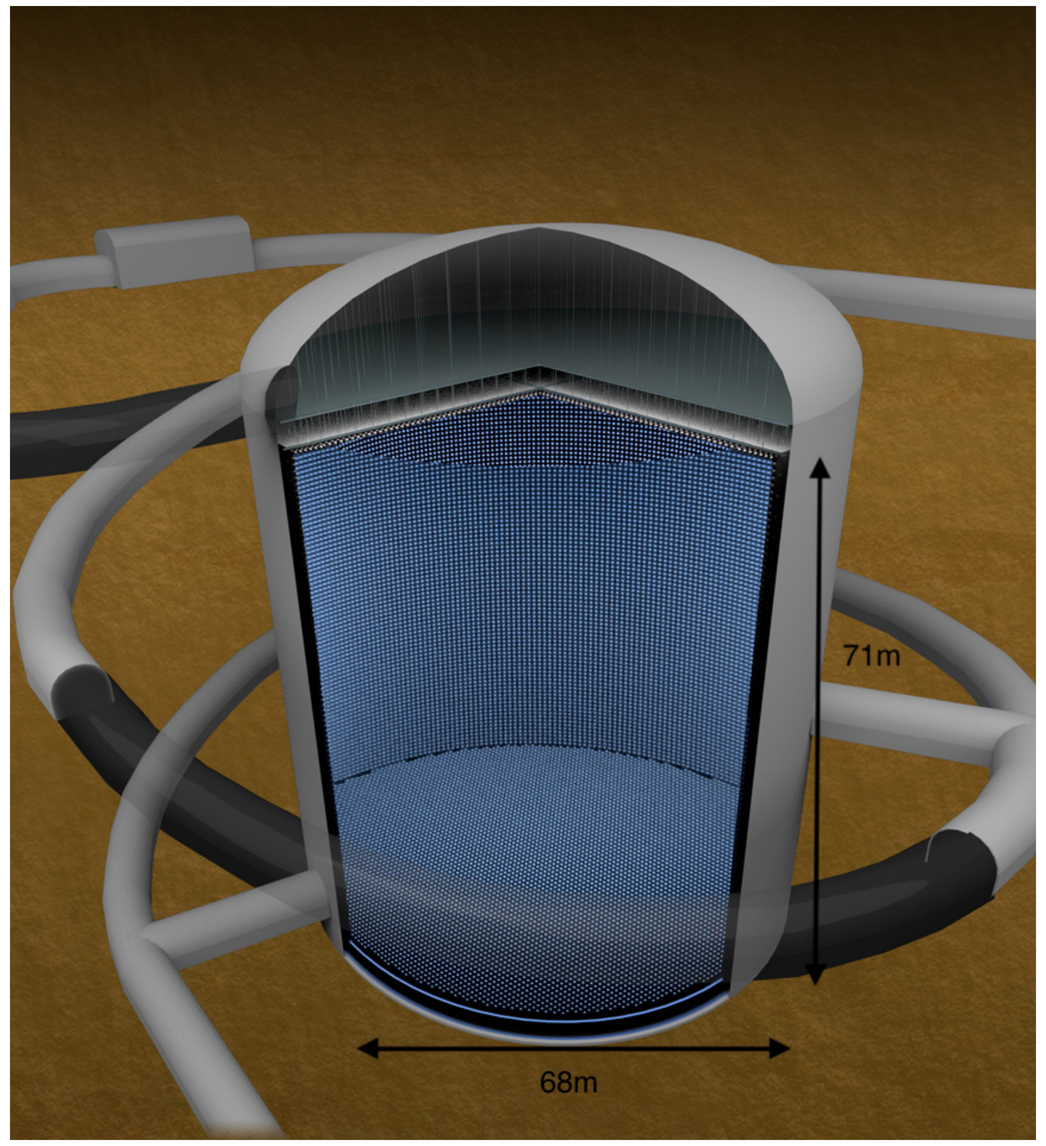


Super-Kamiokande

(1996 - ongoing)

- Proton decay: world best-limit
- Neutrino oscillation (atm/solar/LBL)
  - ➢ All mixing angles and $\Delta m^2 s$

Discovery of neutrino oscillations

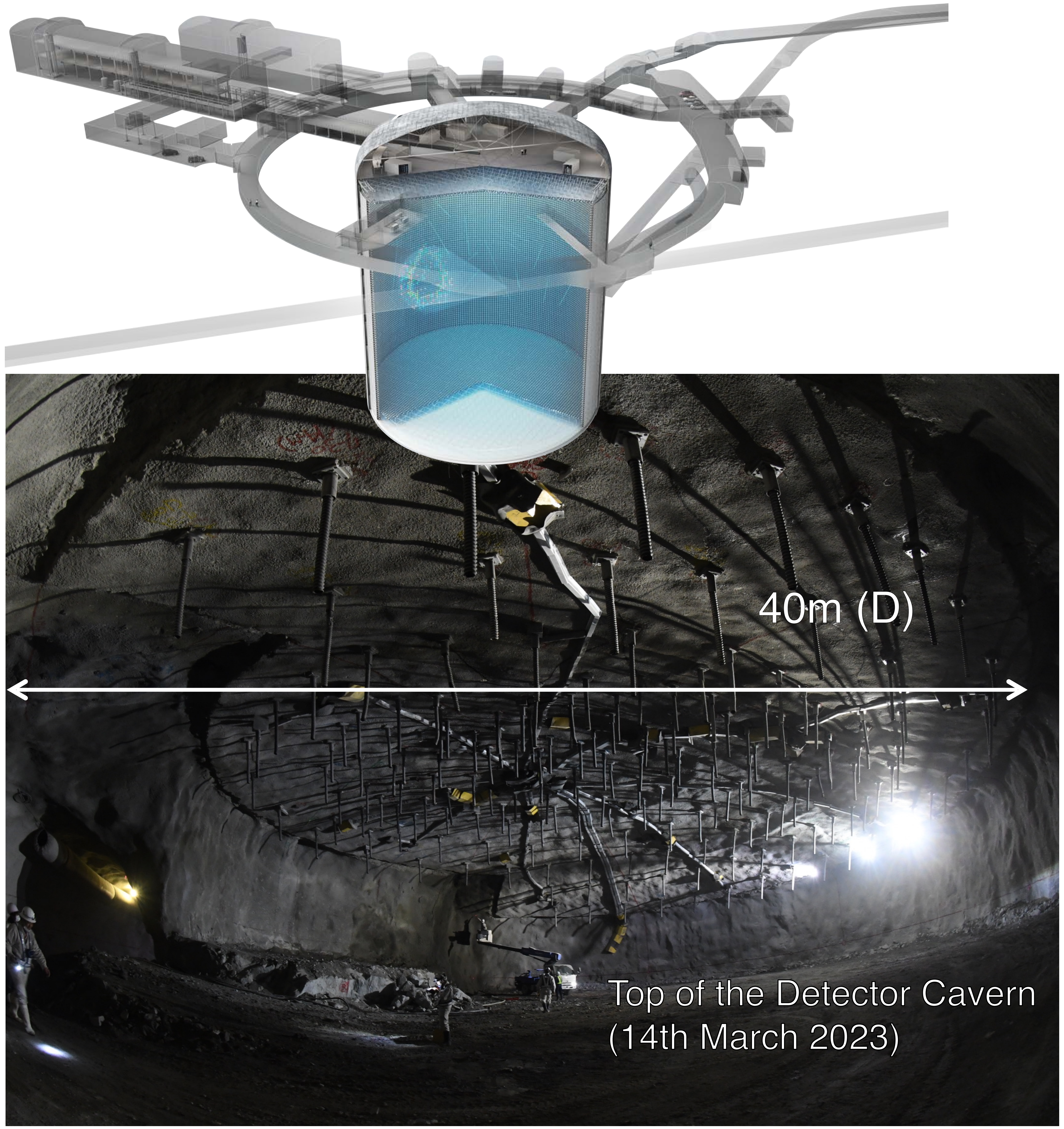


Hyper-Kamiokande
(start operation in 2027)

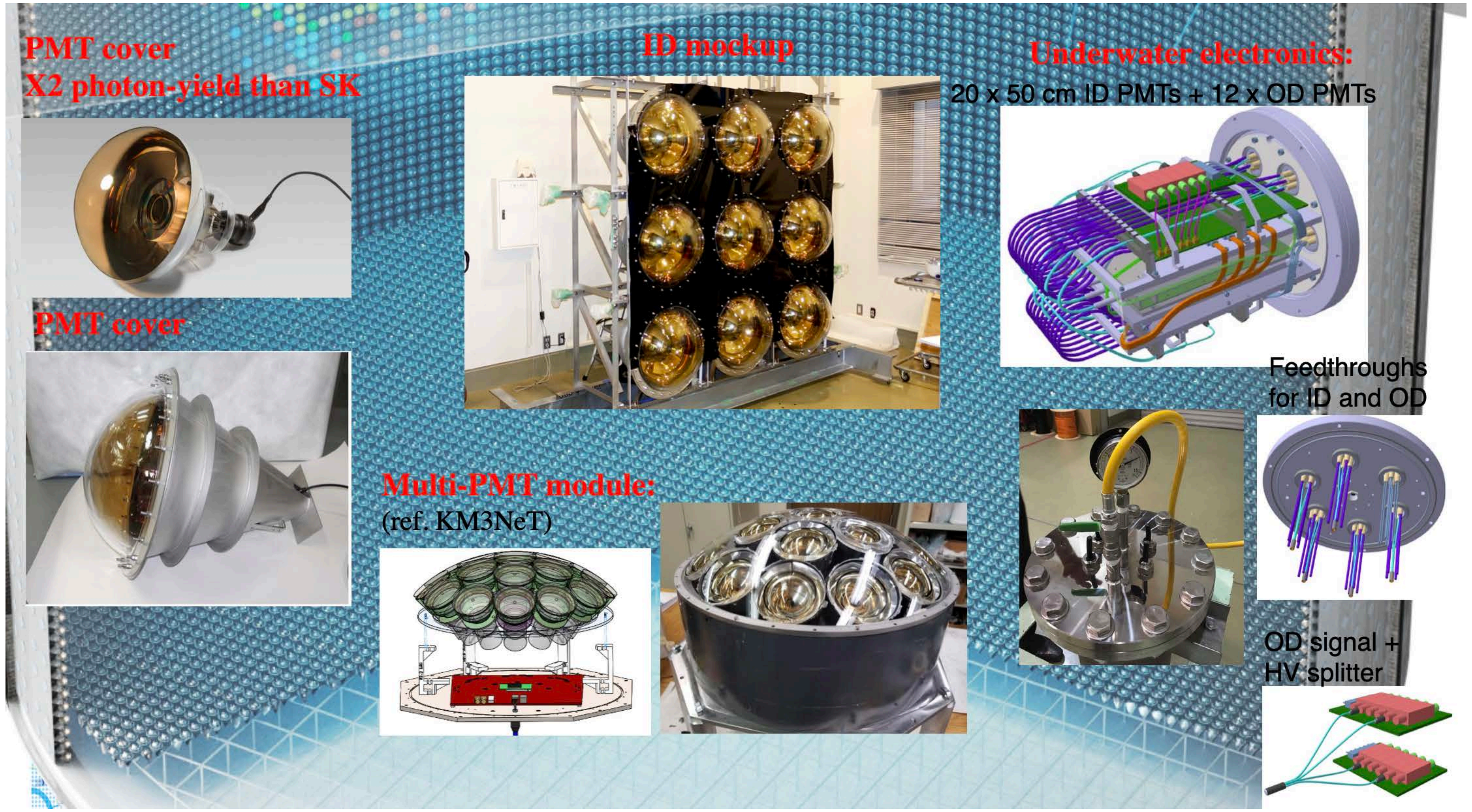
- Extended search for proton decay
- Precision measurement of neutrino oscillation including CPV and MO
- Neutrino astrophysics

Explore new physics

Hyper-K

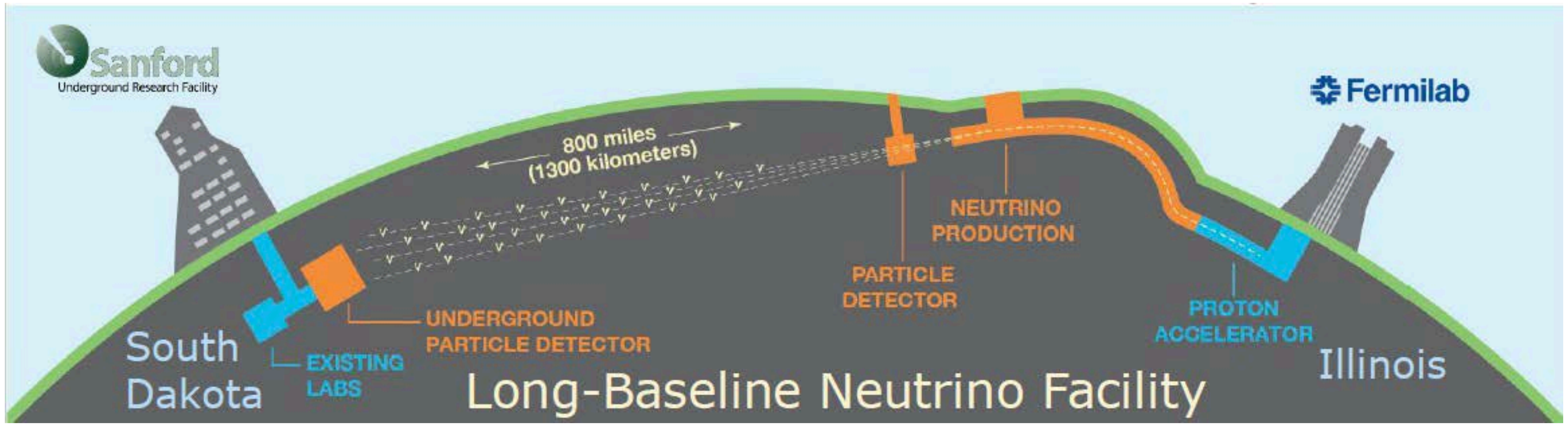


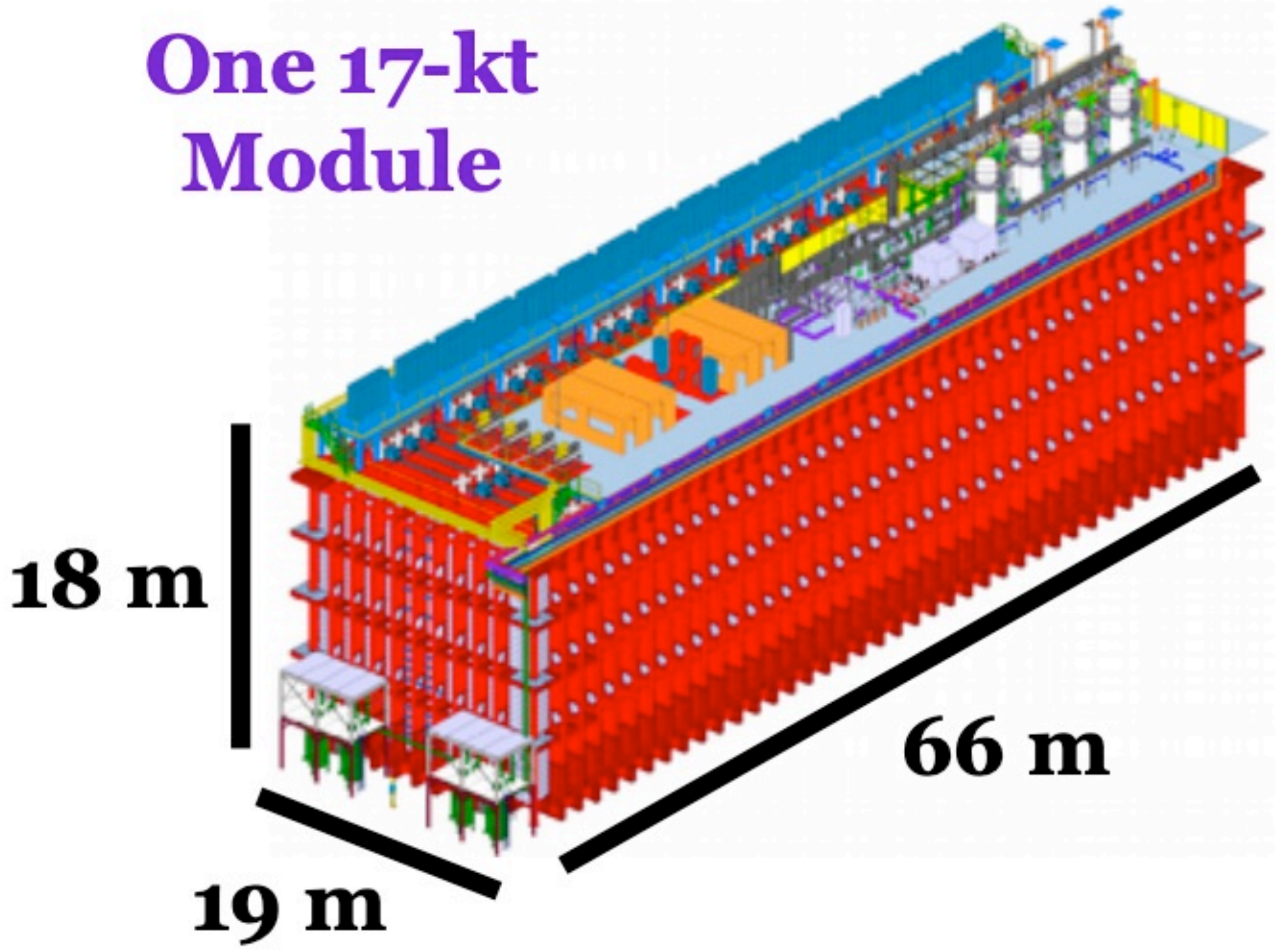
40m (D)
Top of the Detector Cavern
(14th March 2023)

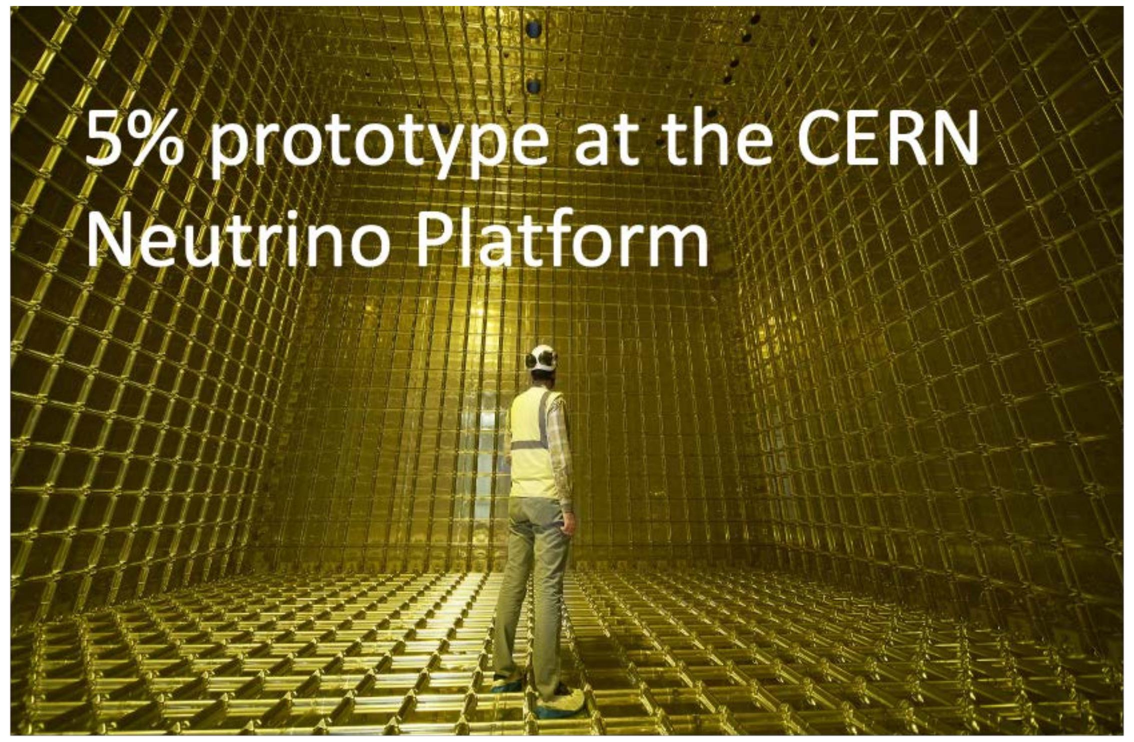


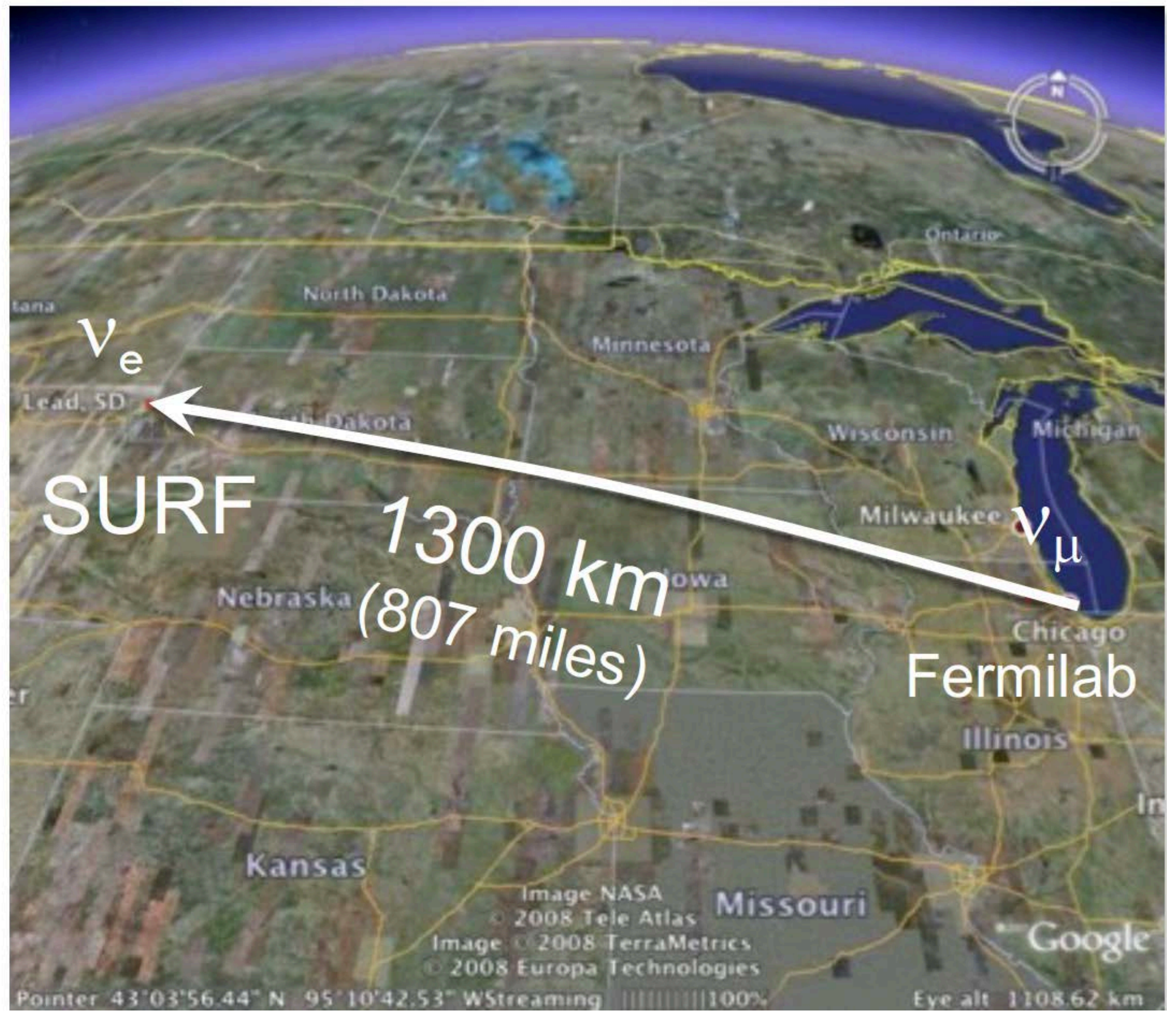
PMT cover
X2 photon-yield than SK
PMT cover
ID mockup
Underwater electronics:
20 x 50 cm ID PMTs + 12 x OD PMTs
Feedthroughs
for ID and OD
Multi-PMT module:
(ref. KM3NeT)
OD signal +
HV splitter

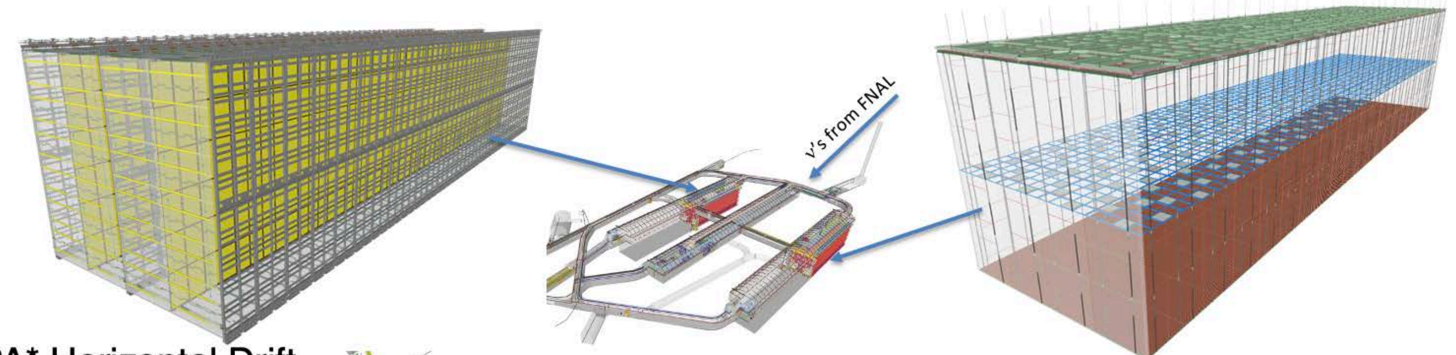
DUNE - Deep Underground Neutrino Experiment











APA* Horizontal Drift

*Anode Plane Assemblies

CRP** Vertical Drift

**Charge Readout Planes

<u>Phase I</u>: near + far site infrastructure, upgradeable
1.2 MW beam, 2x18 kt LArTPC,
movable ND + m catcher, on-axis ND
<u>Phase II</u>: two more FD modules, >2 MW beam,
ND upgrades [new ideas!]
Broad physics program

DUNE and Mass Ordering

DUNE ν_e and $\overline{\nu}_e$ spectra can distinguish mass ordering in Phase I

Data points show NO, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

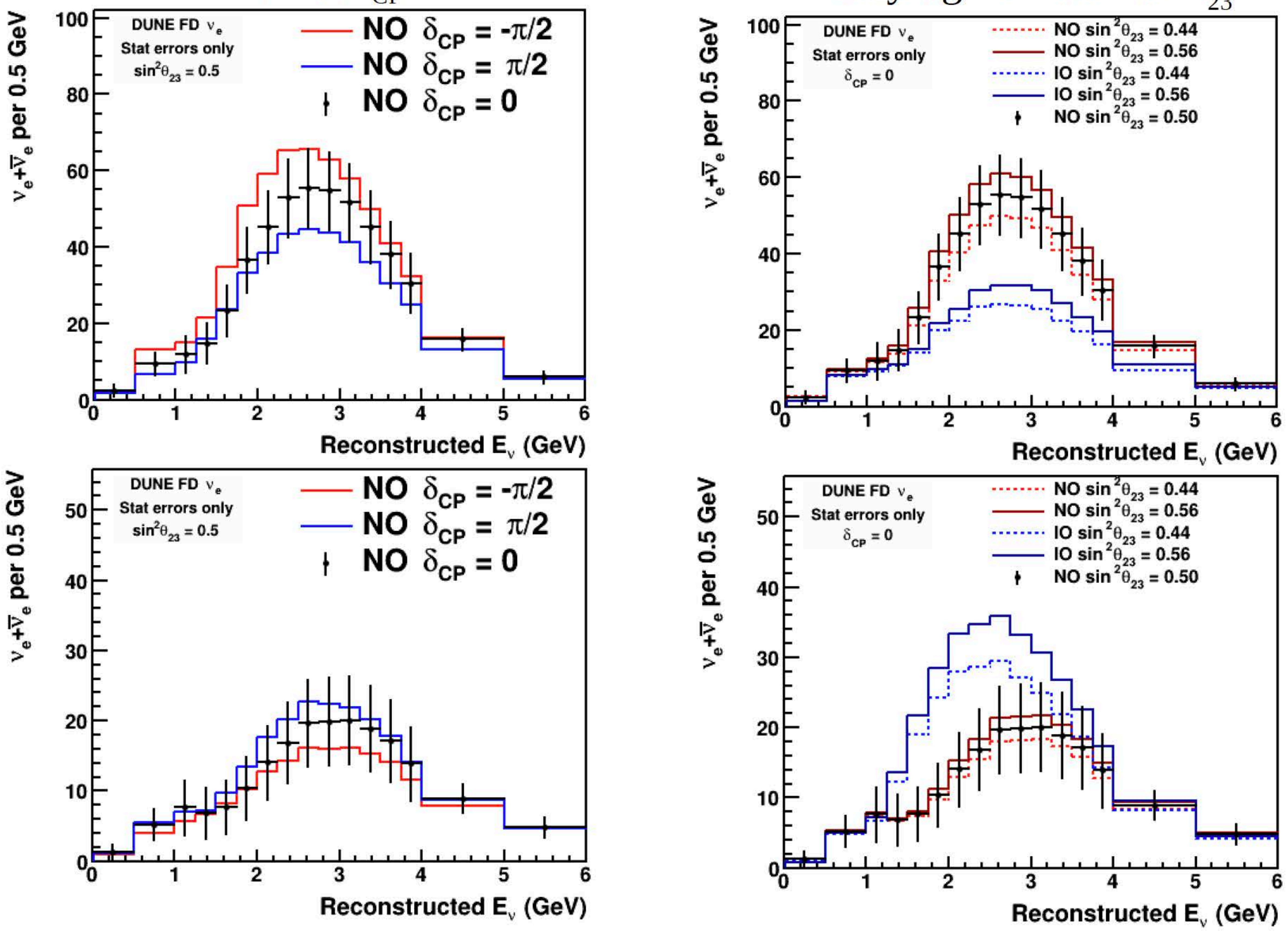
Neutrino mode

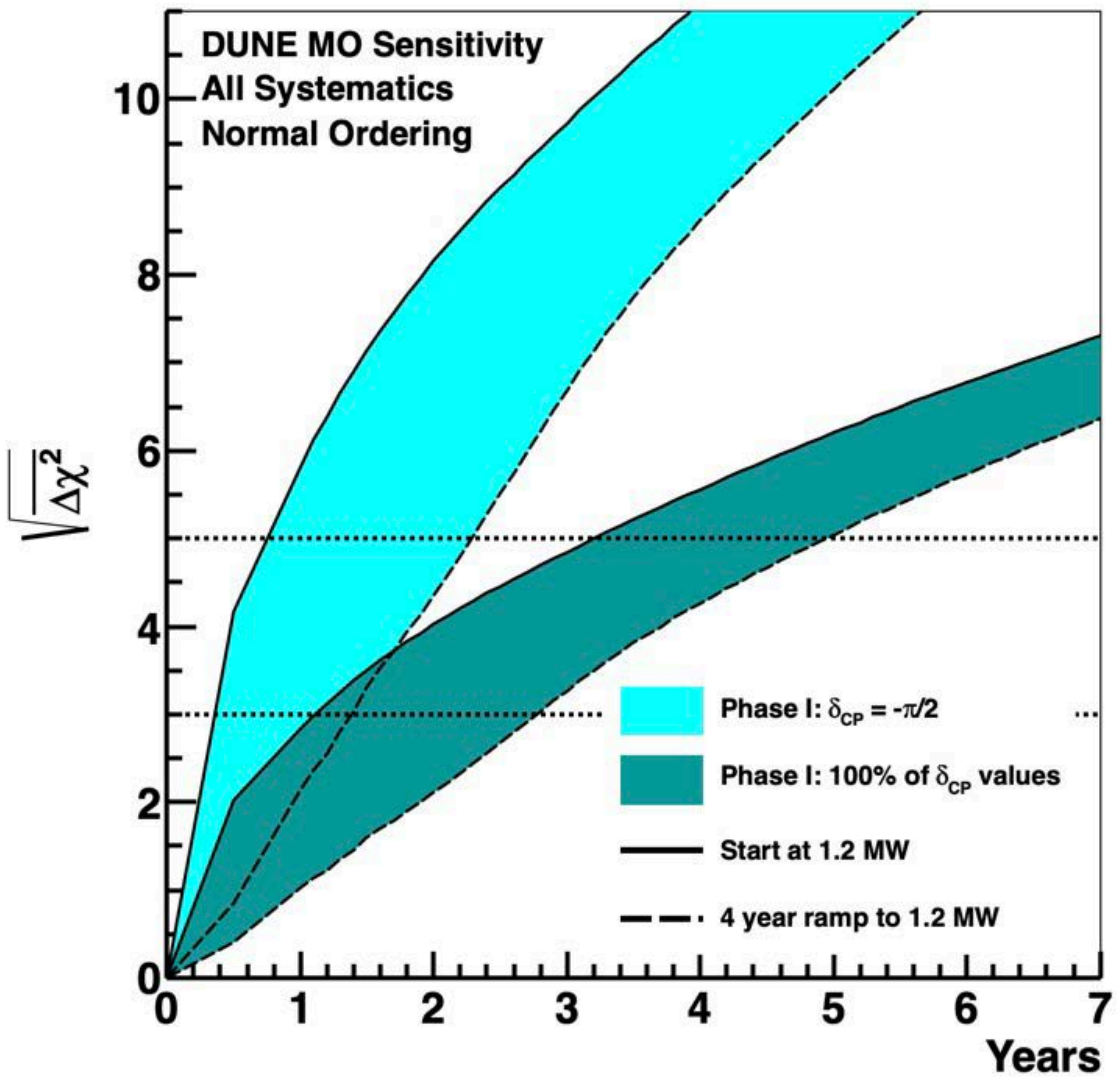
Phase I

Antineutrino mode

Varying δ_{CP}

Varying MO and $\sin^2\theta_{23}$





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DUNE and CP Violation

DUNE ν_e and $\overline{\nu_e}$ spectra can measure δ_{CP} and θ_{23} octant in Phase II

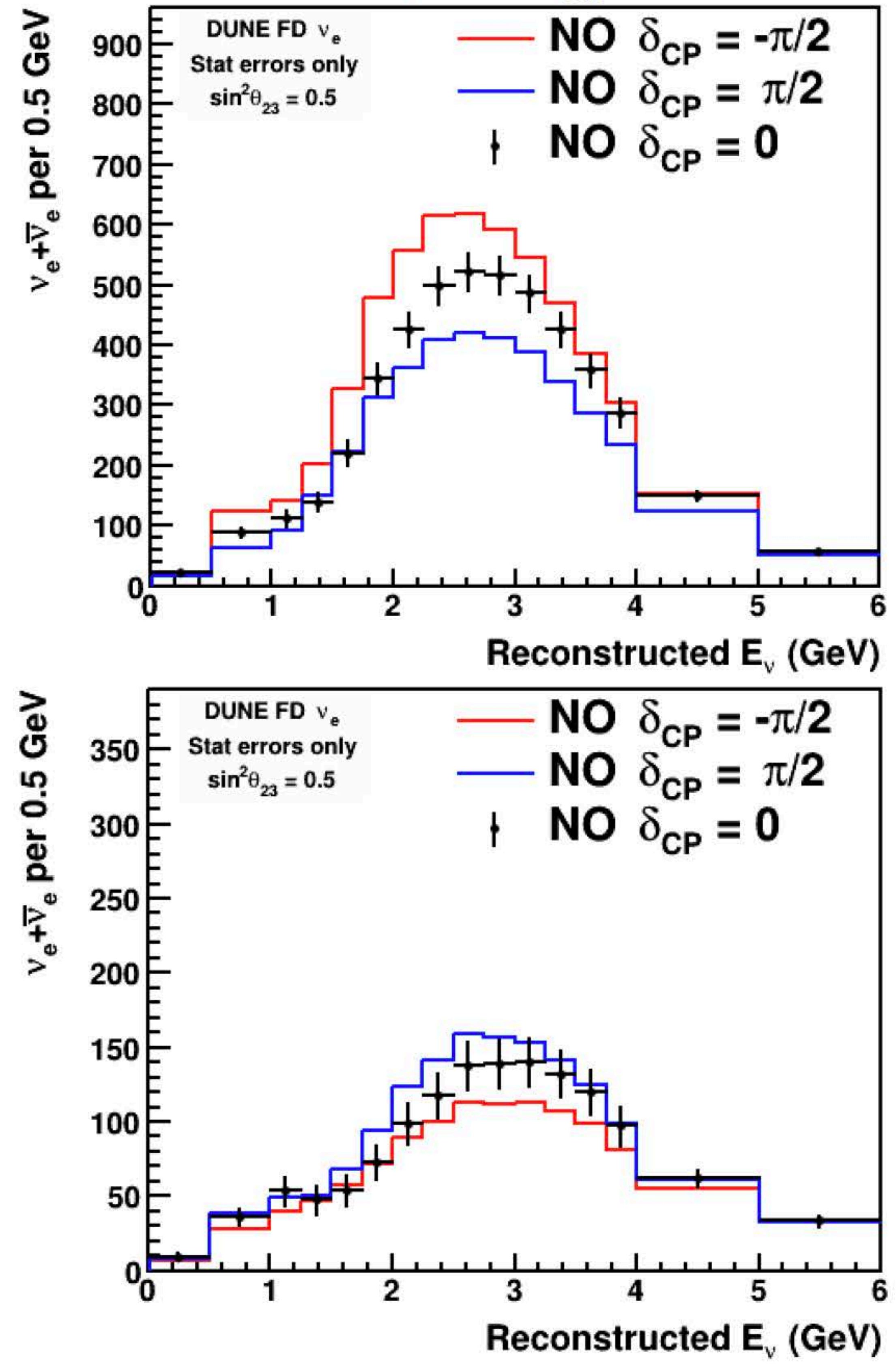
Data points show NO, δ_{CP} = 0, $\sin^2\theta_{23}$ = 0.5

Neutrino mode

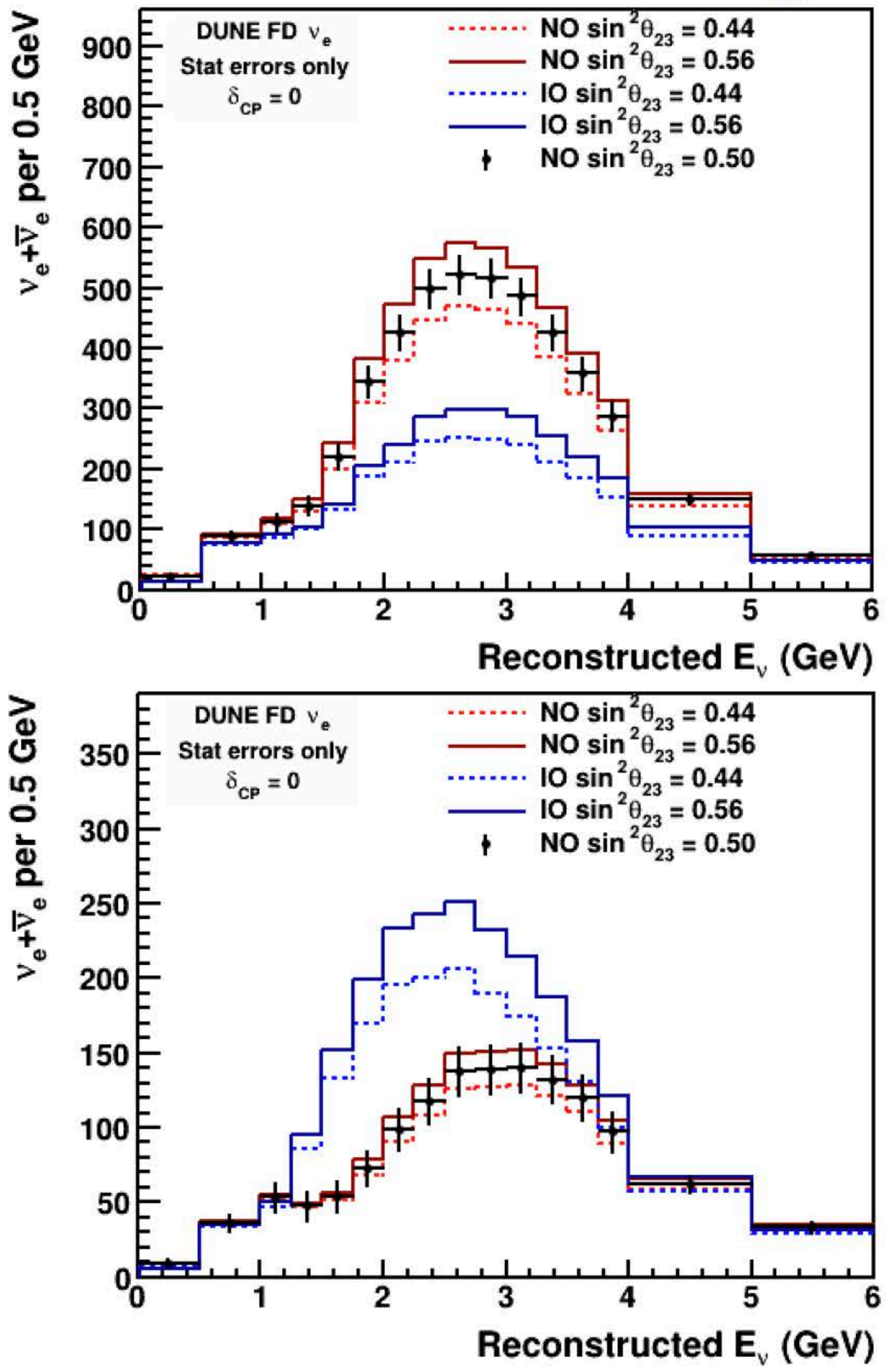
Phase II

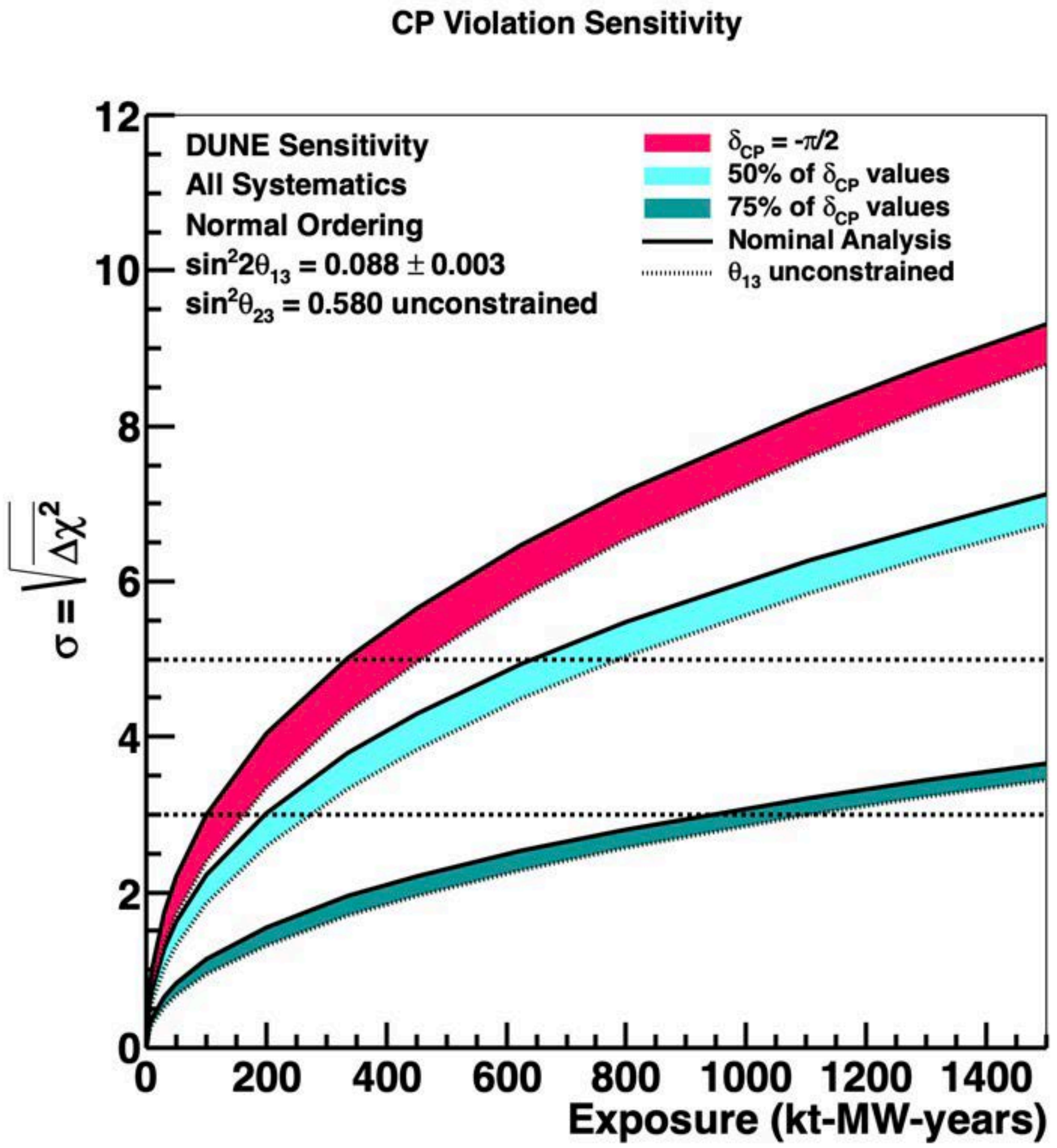
Antineutrino mode

Varying δ_{CP}



Varying MO and $\sin^2\theta_{23}$





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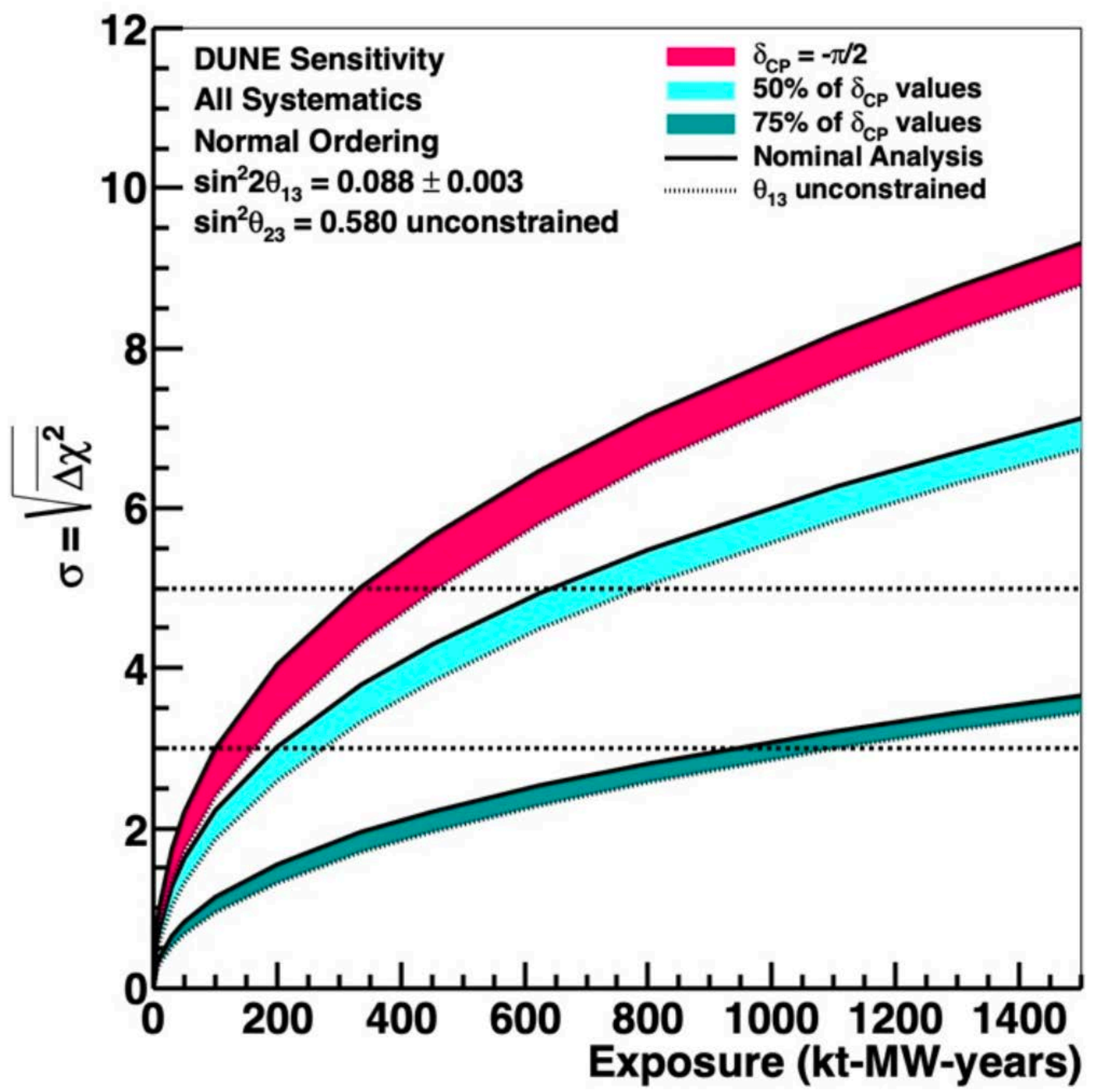
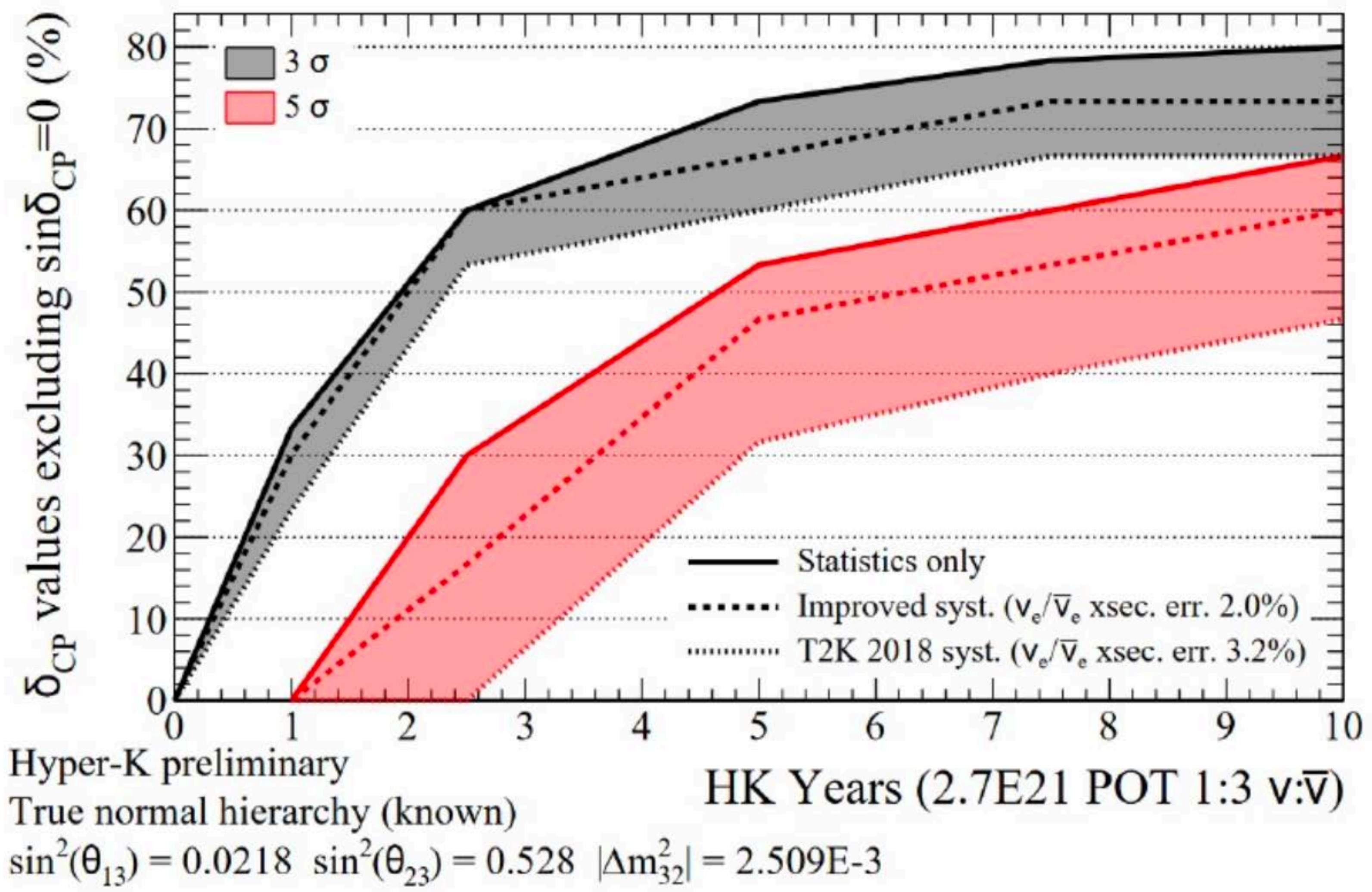
The Quest for CP Violation





When will CP violation be established?

- Assuming that JUNO determines the mass ordering at 3σ by 2030, Hyper-K data begi… Phase II is
- If δ_{CP}… at 5σ in 20…
- If δ_{CP}… at 5σ in be… matics, with DUNE mass ordering)
- If δ_{CP}… DUN… signi… er-K comb…
- If δ_{CP}… Hype…
- If $\delta_{CP} = 0°$, then DUNE and Hyper-K will measure δ_{CP} with a precision of ~6°

Nature is very kind:
Hyper-K establishes CPV
with mass ordering from JUNO (3σ)
or DUNE (5σ)

Nature is less kind:
DUNE and Hyper-K are competitive,
and both may be required

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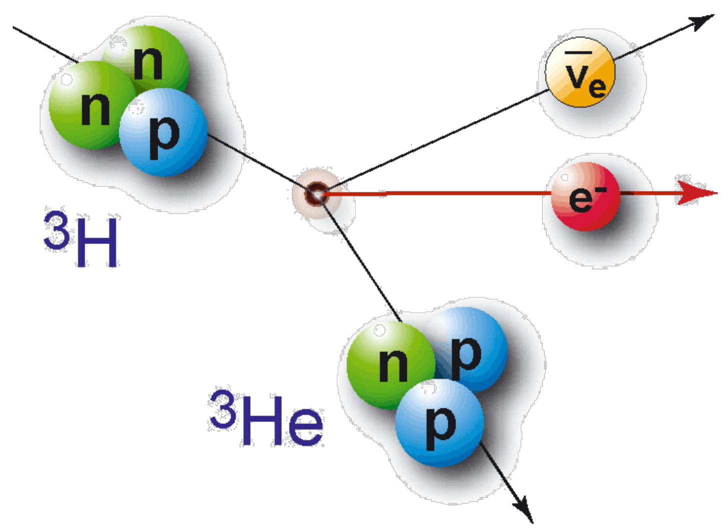
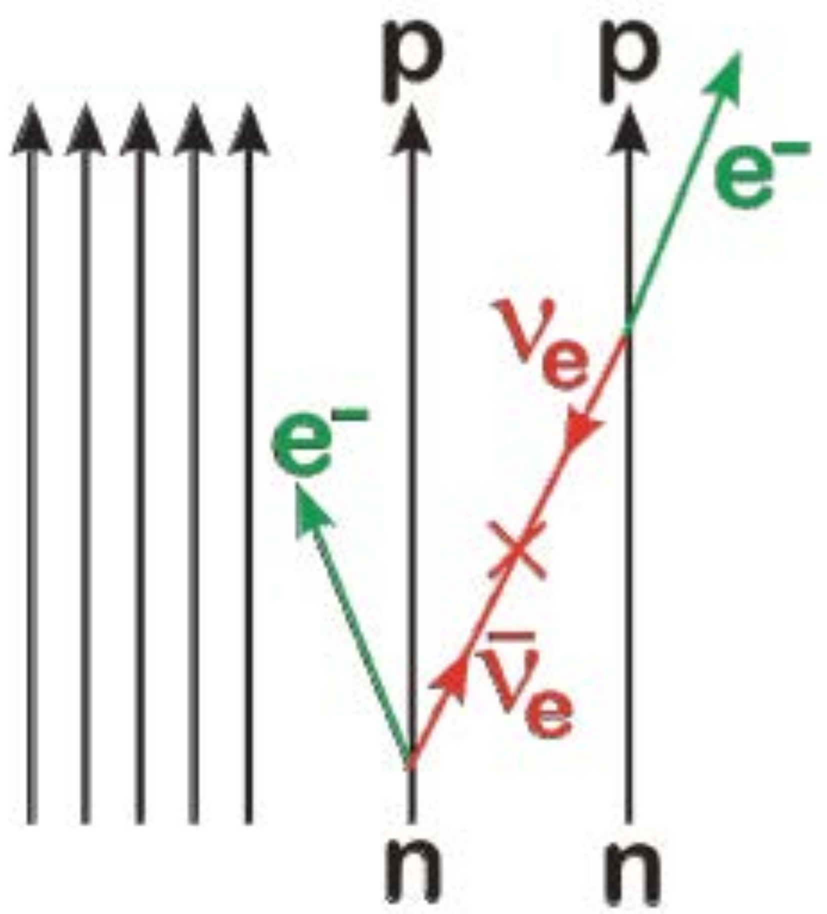
Summary and Outlook

ν experiments provide key insight into the nature of neutrinos and physics beyond the SM



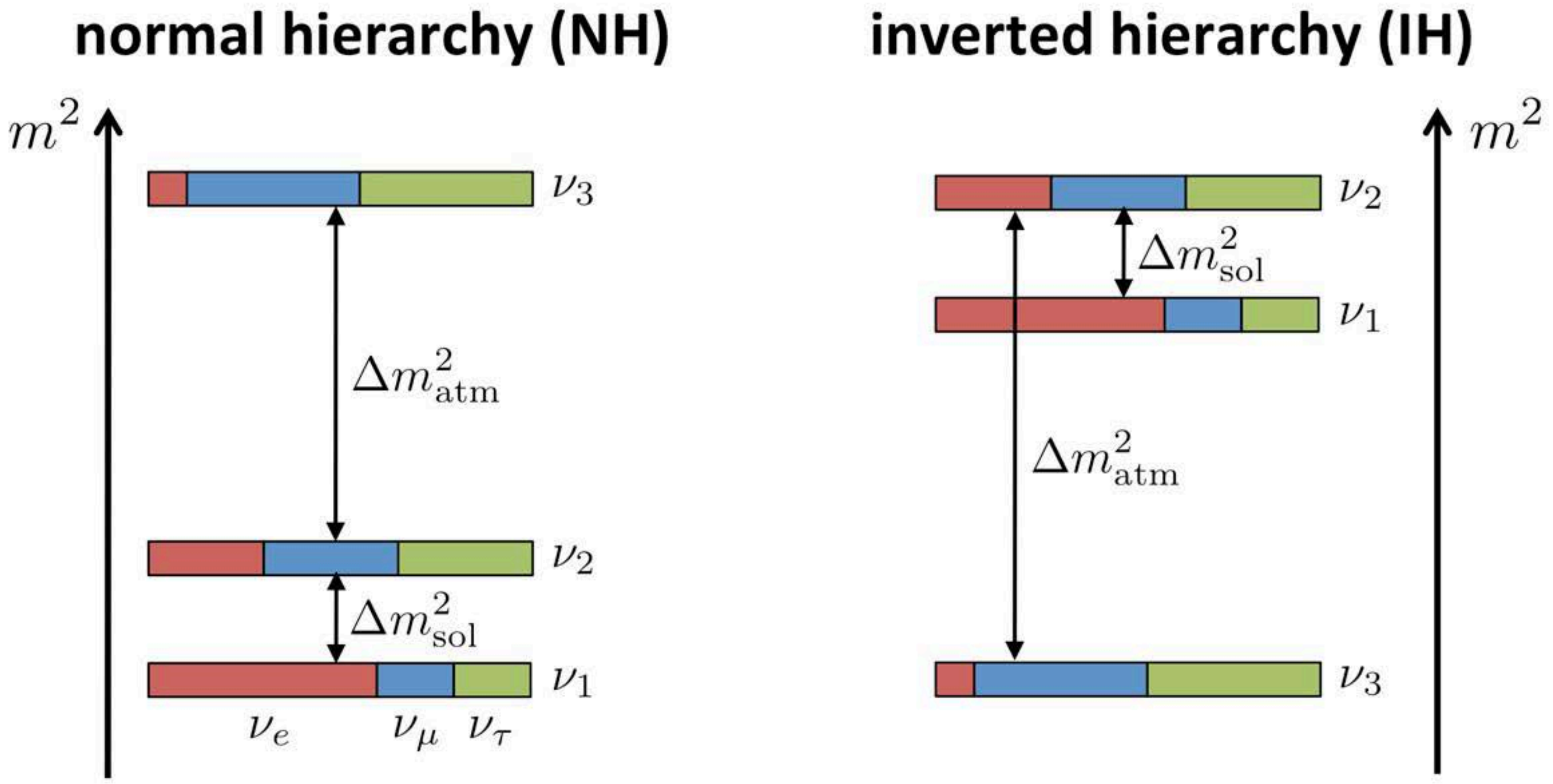
Beta decay allow direct neutrino mass measurements

Aim to reach $m_\nu < 0.04$ eV



Neutrinoless double beta (0νββ) powerful probe of lepton number violation (ΔL=2).

Would establish lepton number violation and demonstrate that neutrinos are Majorana.



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\mathrm{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Reactor and accelerator experiments will determine mass ordering and probe CP violation.

Precision oscillation measurements will test the 3 flavor paradigm.

Exciting years lie ahead!